



US009496271B2

(12) **United States Patent**
Or-Bach et al.

(10) **Patent No.:** **US 9,496,271 B2**

(45) **Date of Patent:** ***Nov. 15, 2016**

(54) **3DIC SYSTEM WITH A TWO STABLE STATE MEMORY AND BACK-BIAS REGION**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 15 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **14/506,160**

(22) Filed: **Oct. 3, 2014**

(65) **Prior Publication Data**

US 2015/0054090 A1 Feb. 26, 2015

Related U.S. Application Data

(63) Continuation of application No. 13/792,202, filed on Mar. 11, 2013, now Pat. No. 8,902,663.

(51) **Int. Cl.**

H01L 27/115 (2006.01)
G11C 16/02 (2006.01)
H01L 29/78 (2006.01)
G11C 11/404 (2006.01)
G11C 11/4097 (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC **H01L 27/115** (2013.01); **G11C 11/404** (2013.01); **G11C 11/4097** (2013.01); **G11C 16/02** (2013.01); **H01L 27/10802** (2013.01); **H01L 29/78** (2013.01); **H01L 29/7841** (2013.01); **G11C 11/412** (2013.01); **G11C 16/0483** (2013.01); **G11C 2213/71** (2013.01)

(58) **Field of Classification Search**

CPC G11C 11/412; G11C 11/417; G11C 8/16; G11C 11/40; H01L 29/7841; H01L 27/10802; H01L 27/085

USPC 365/51, 63, 185.18, 72; 257/499, 257/E23.145, 774, 401

See application file for complete search history.

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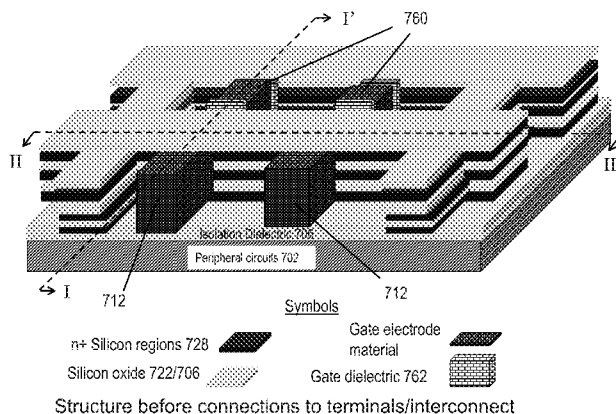
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(57) **ABSTRACT**

A 3D IC based system, including: a first layer including first transistors; a second layer overlying the first layer, the second layer includes a plurality of second transistors, where the second layer includes at least one through second layer via having a diameter of less than 400 nm, and where at least one of the plurality of second transistors forms a two stable state memory cell including a back-bias region.

20 Claims, 133 Drawing Sheets



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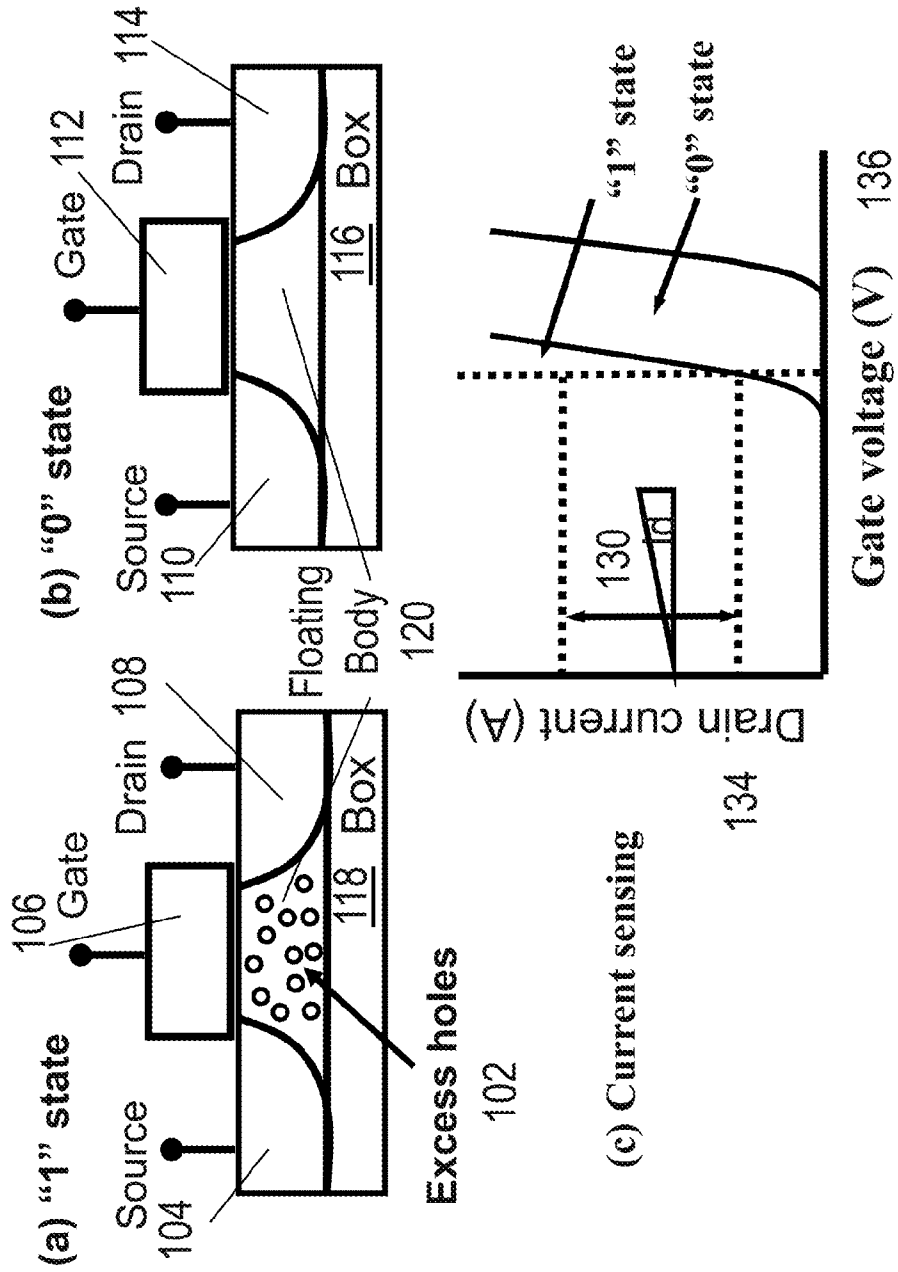
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Fig. 1



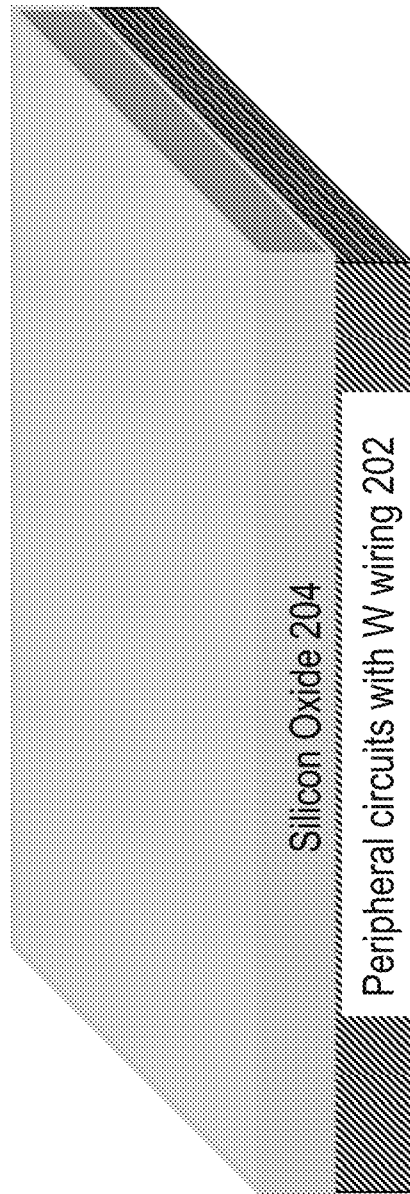


Fig. 2A

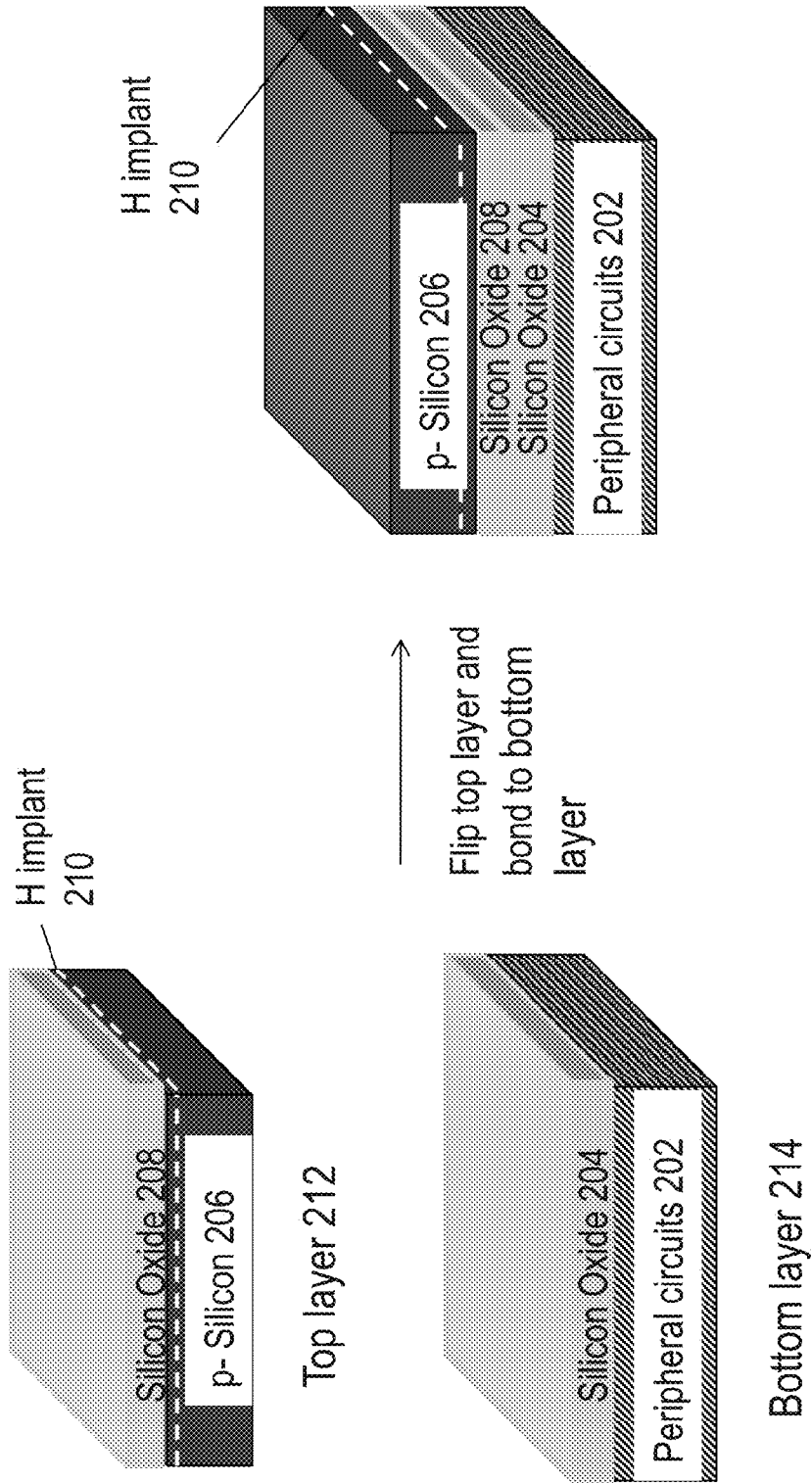


Fig. 2B

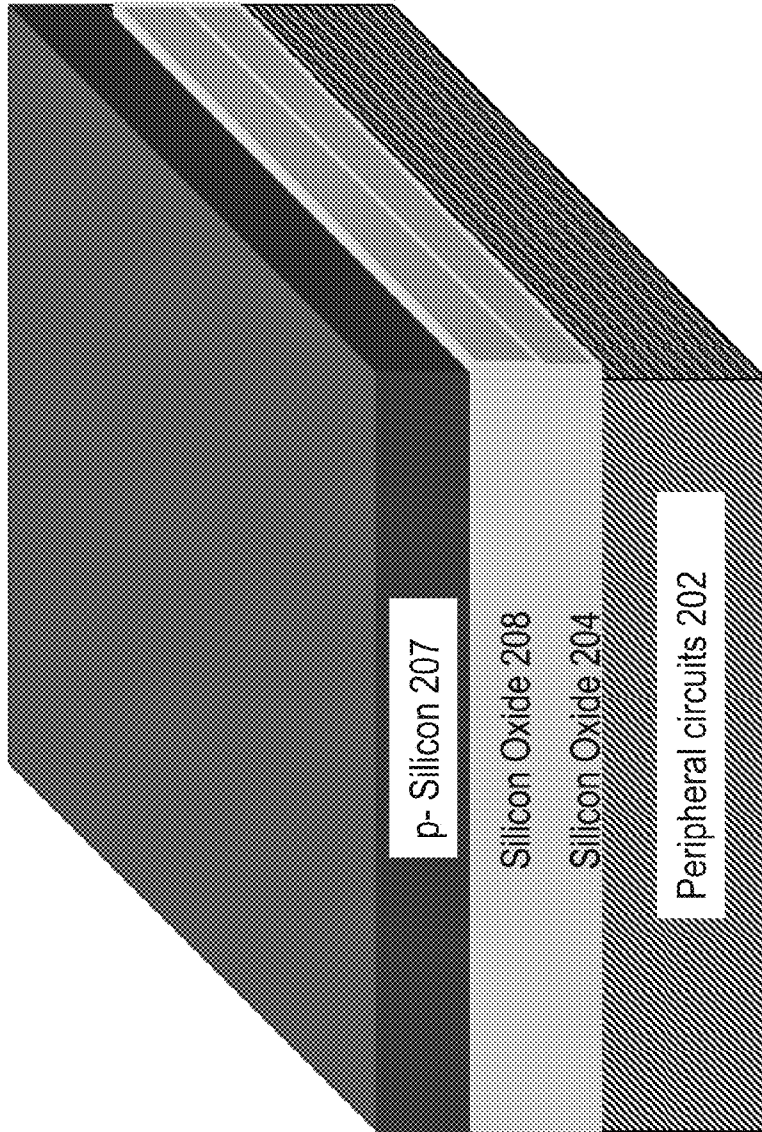


Fig. 2C

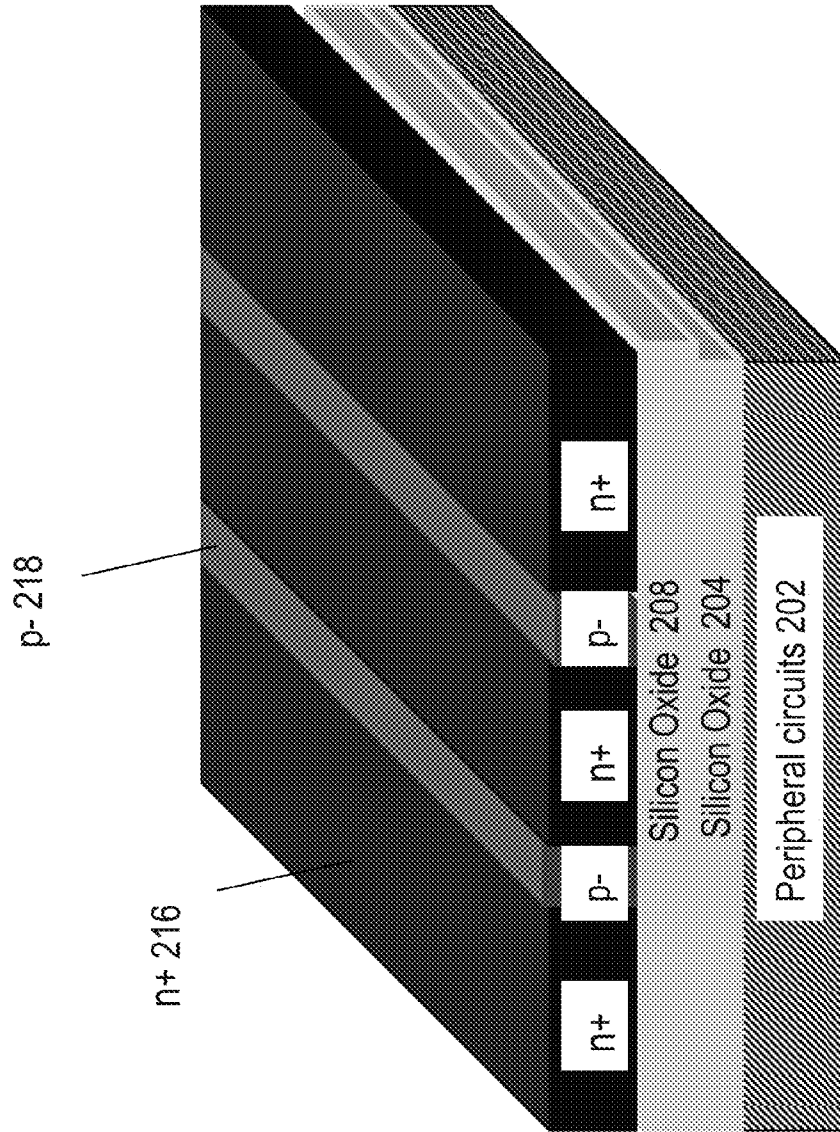


Fig. 2D

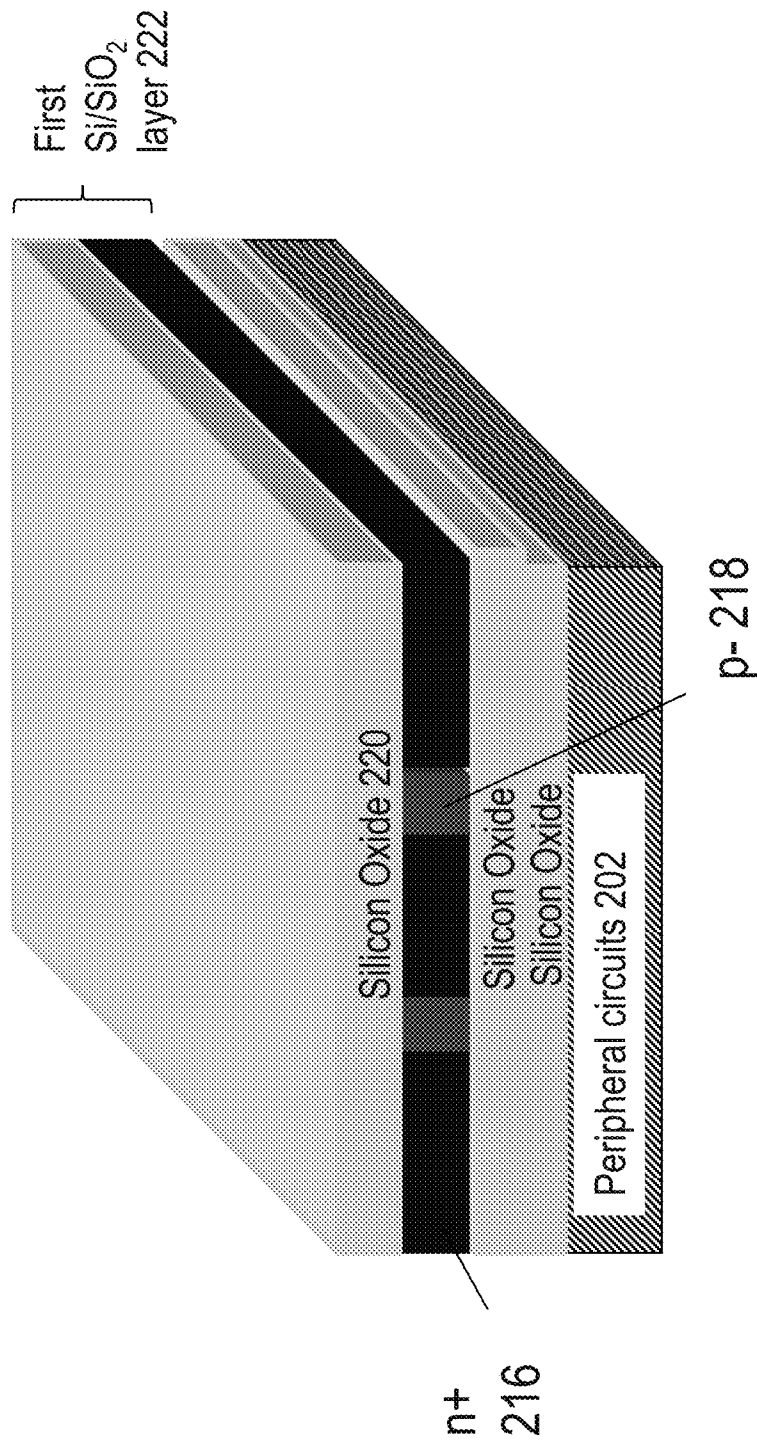


Fig. 2E

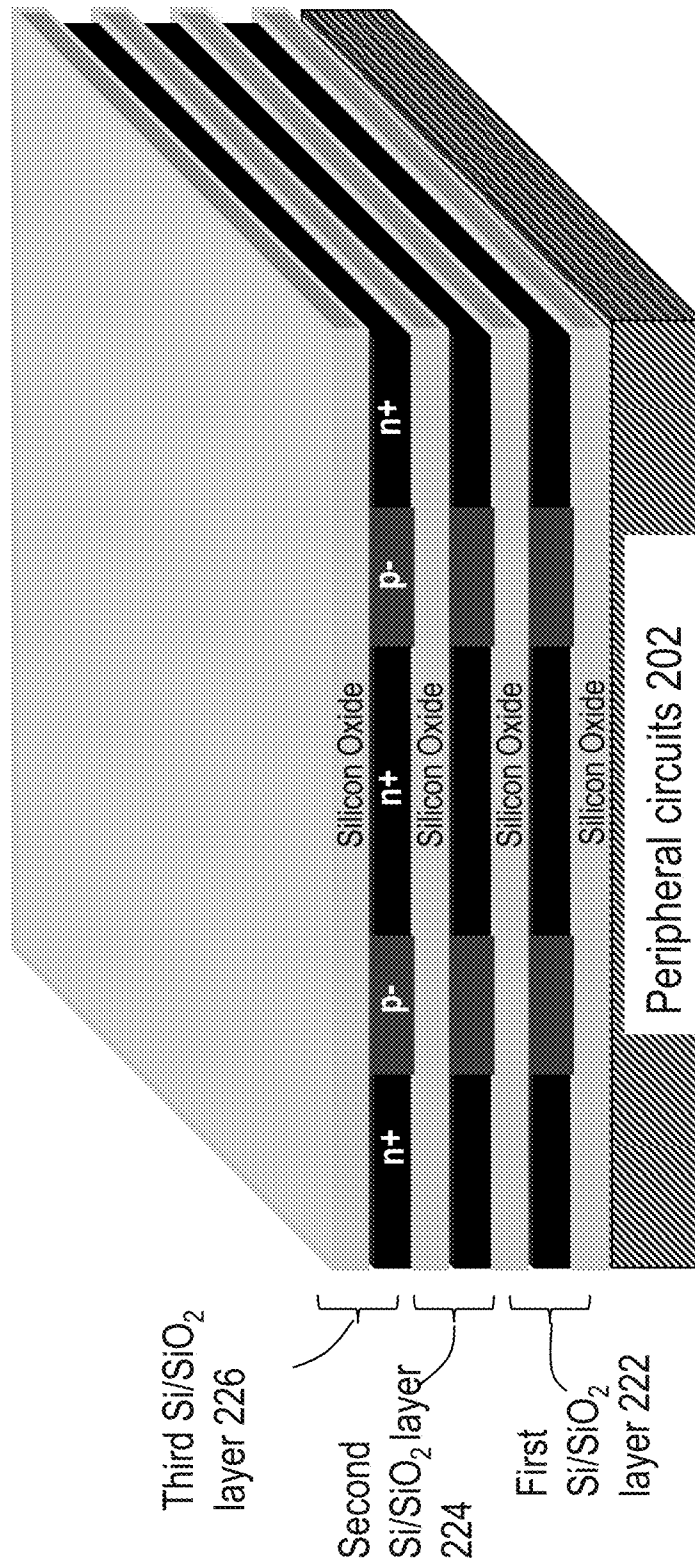


Fig. 2F

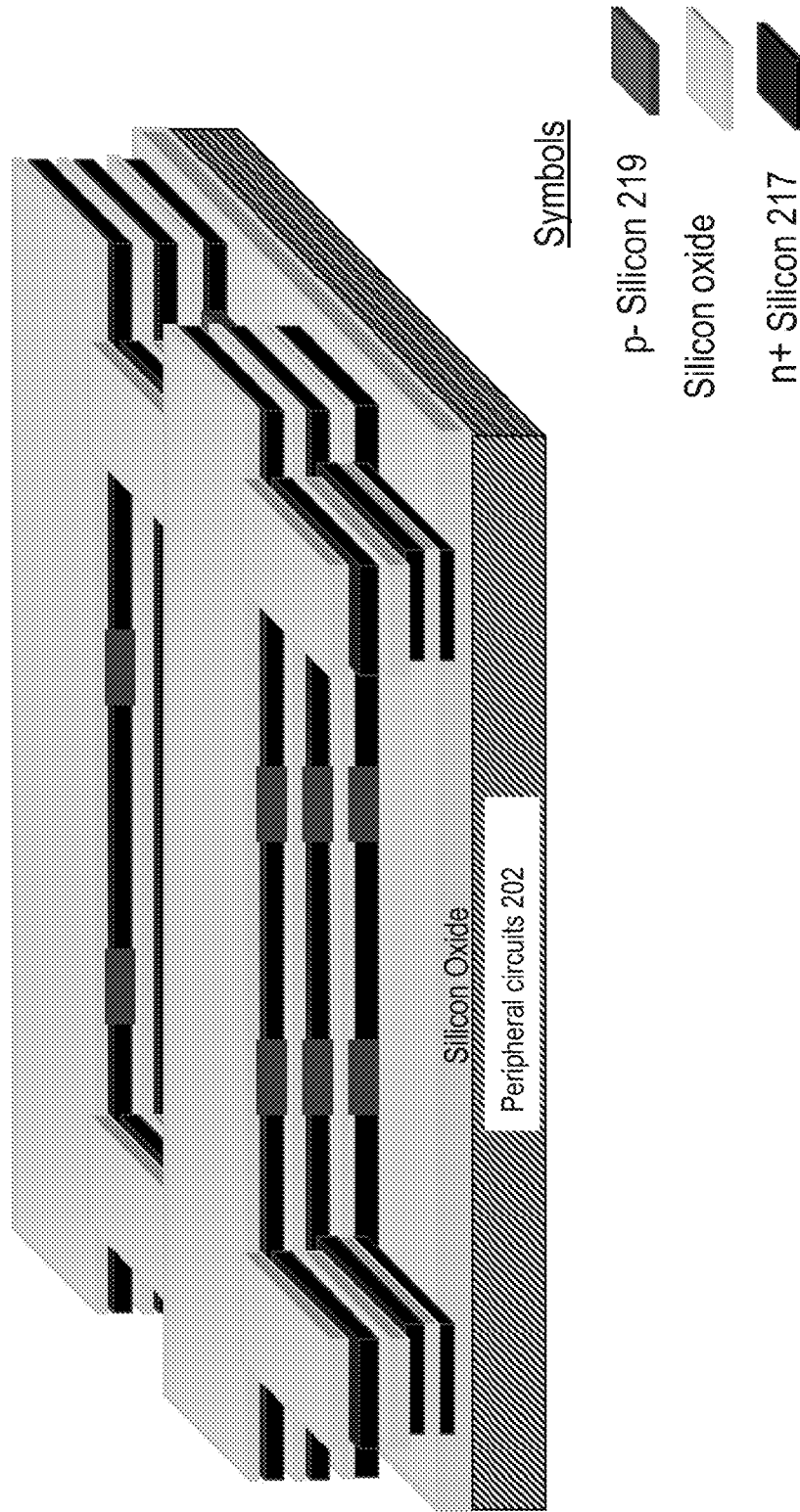


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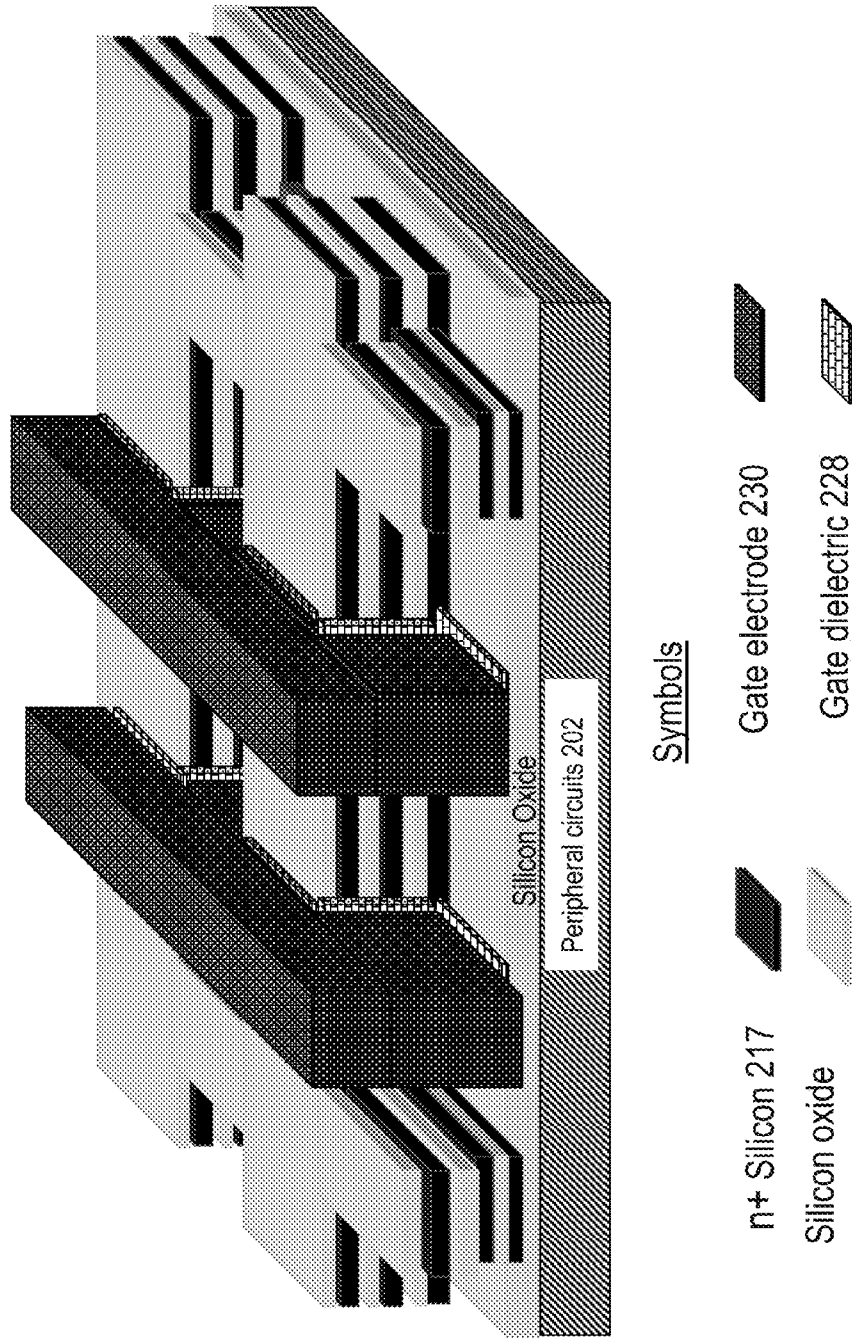


Fig. 2H

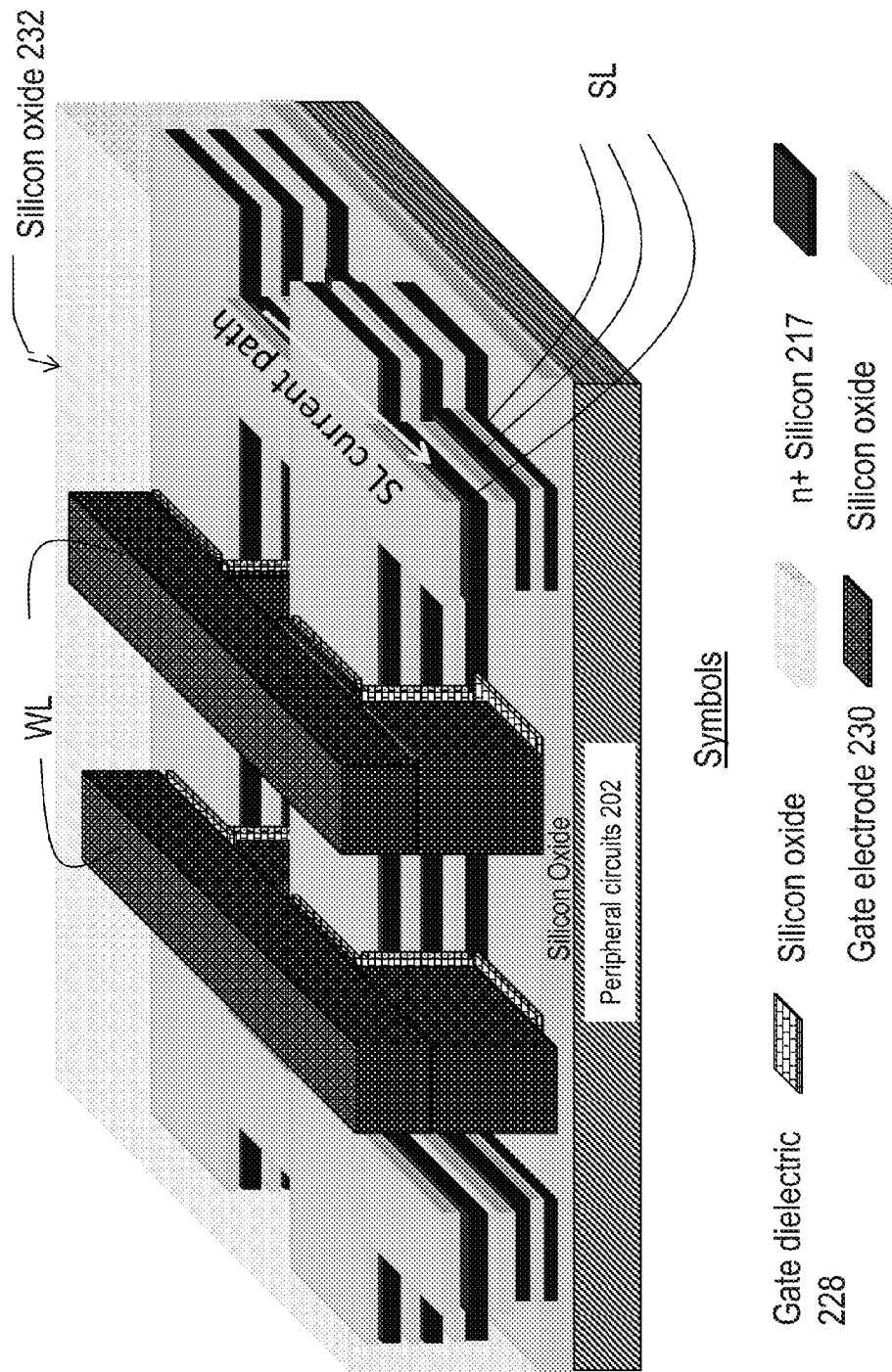


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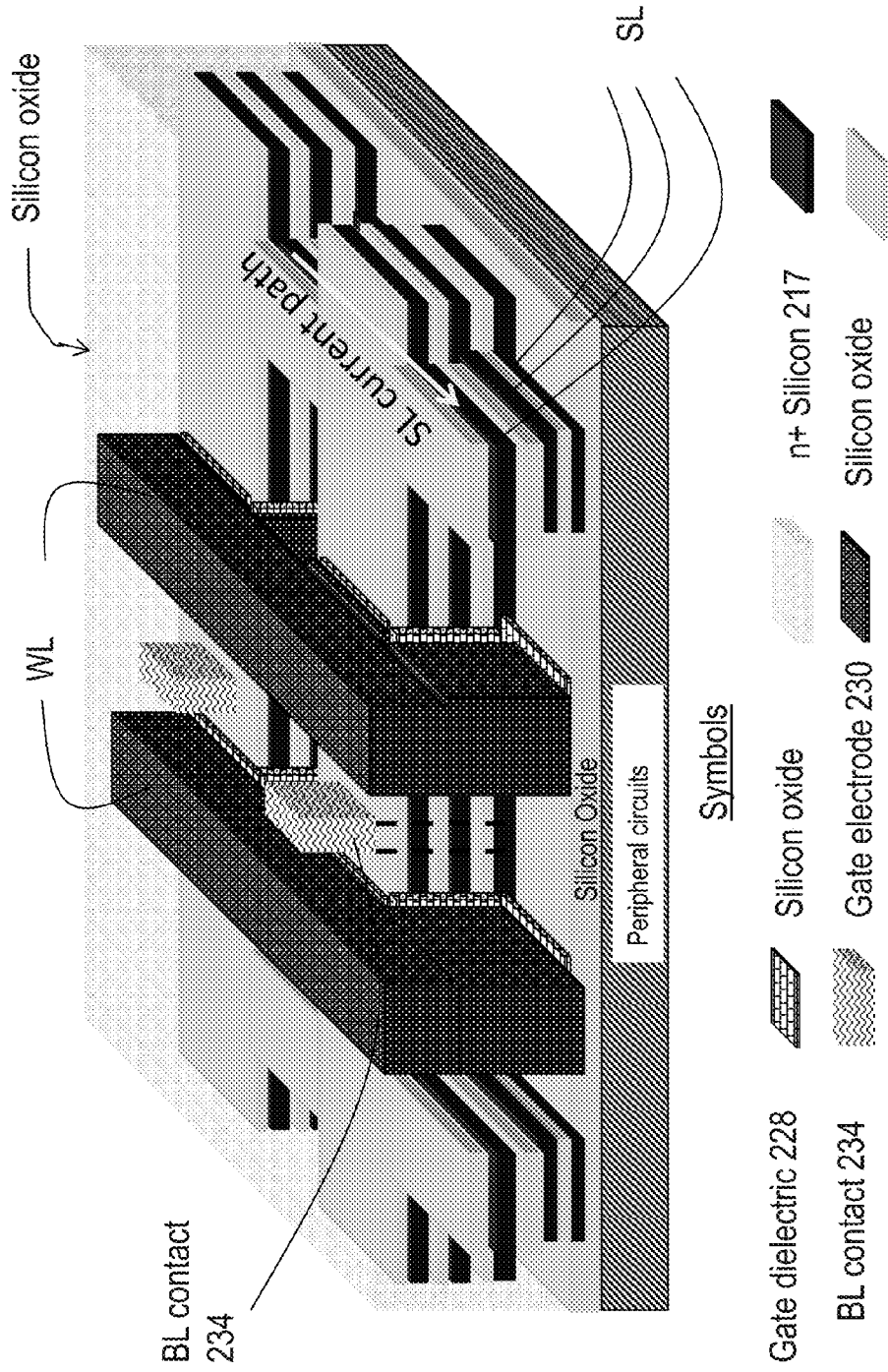


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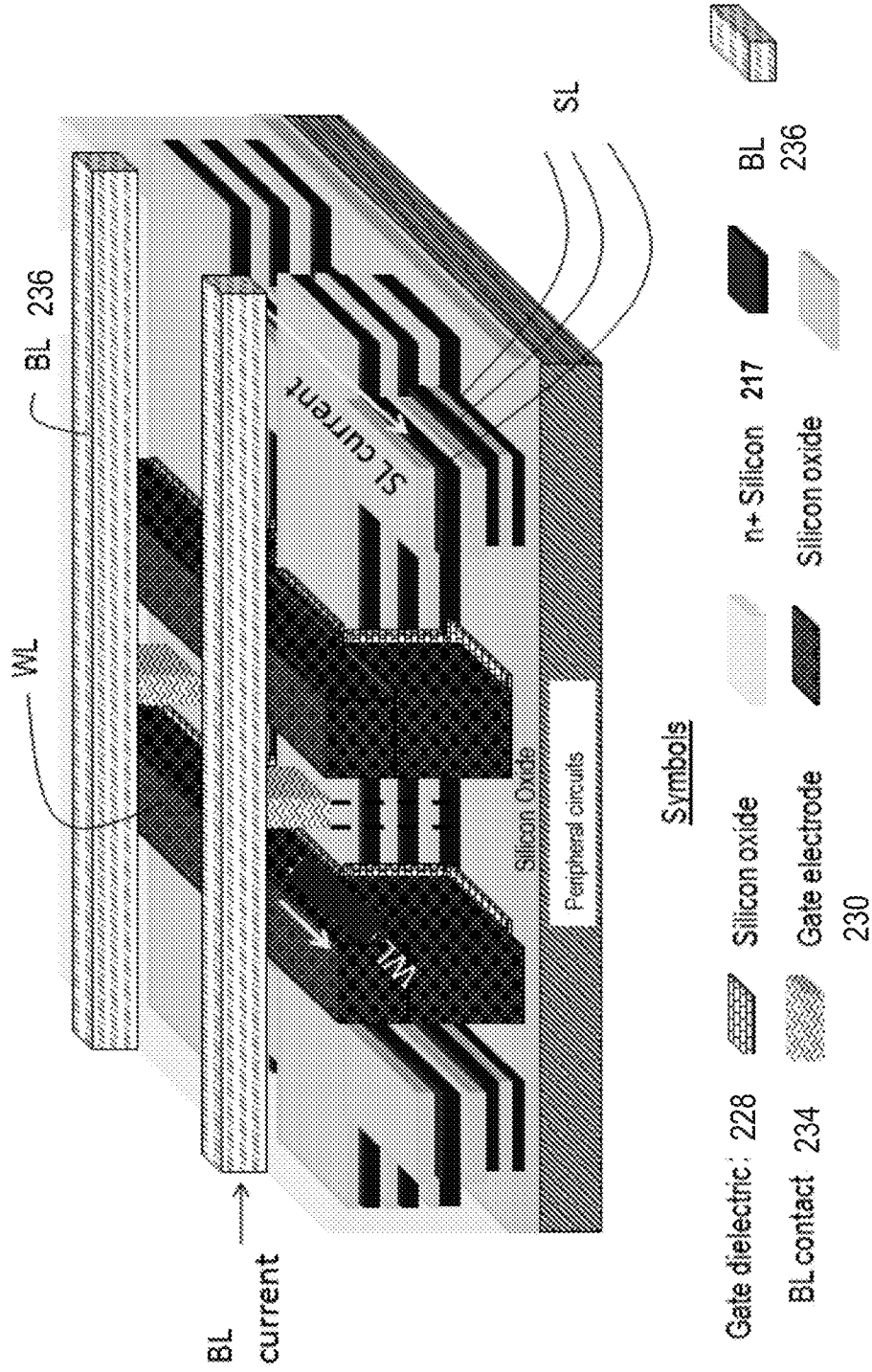
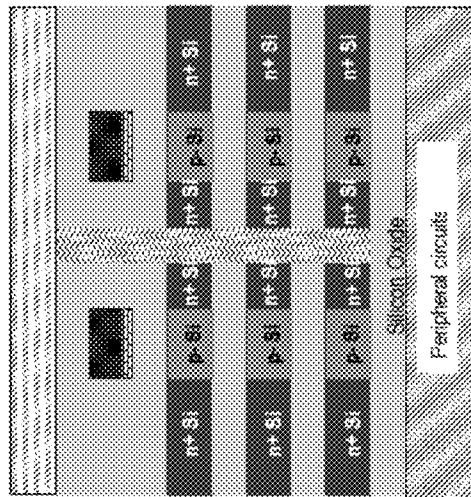
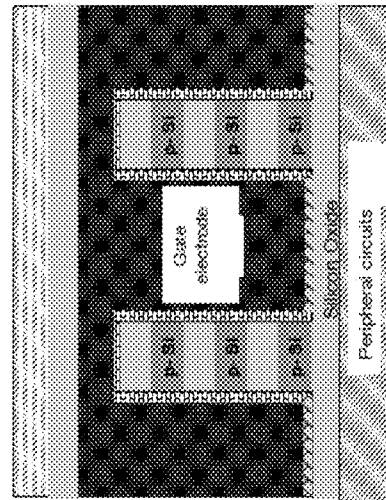


Fig. 2K



View along II plane



View along III plane

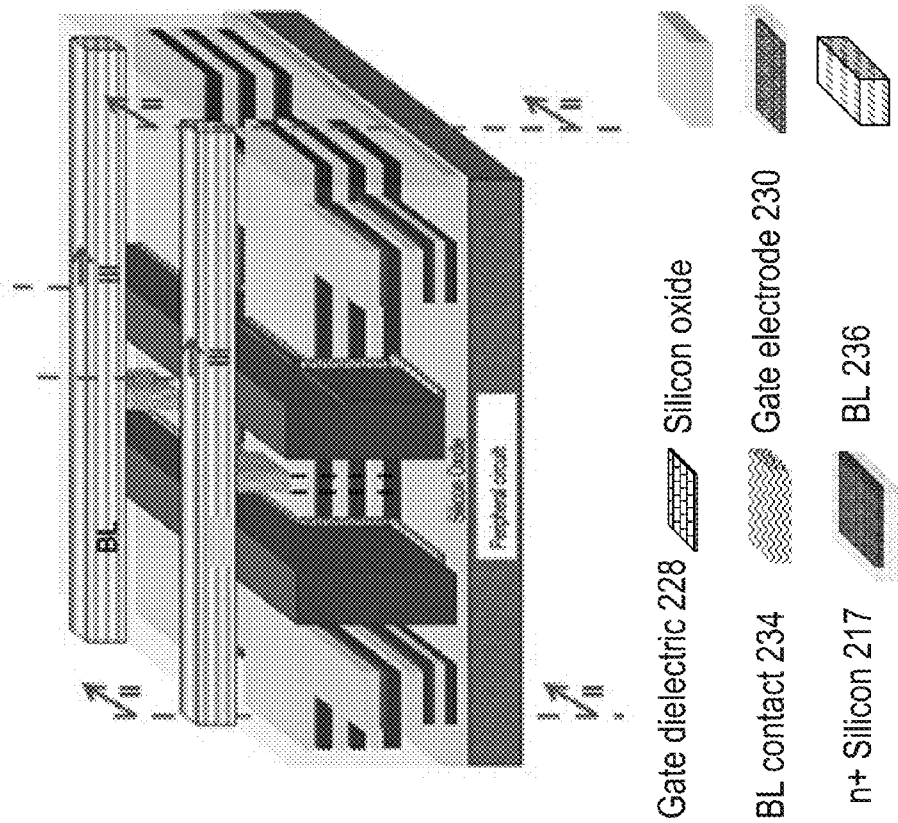


Fig. 2L

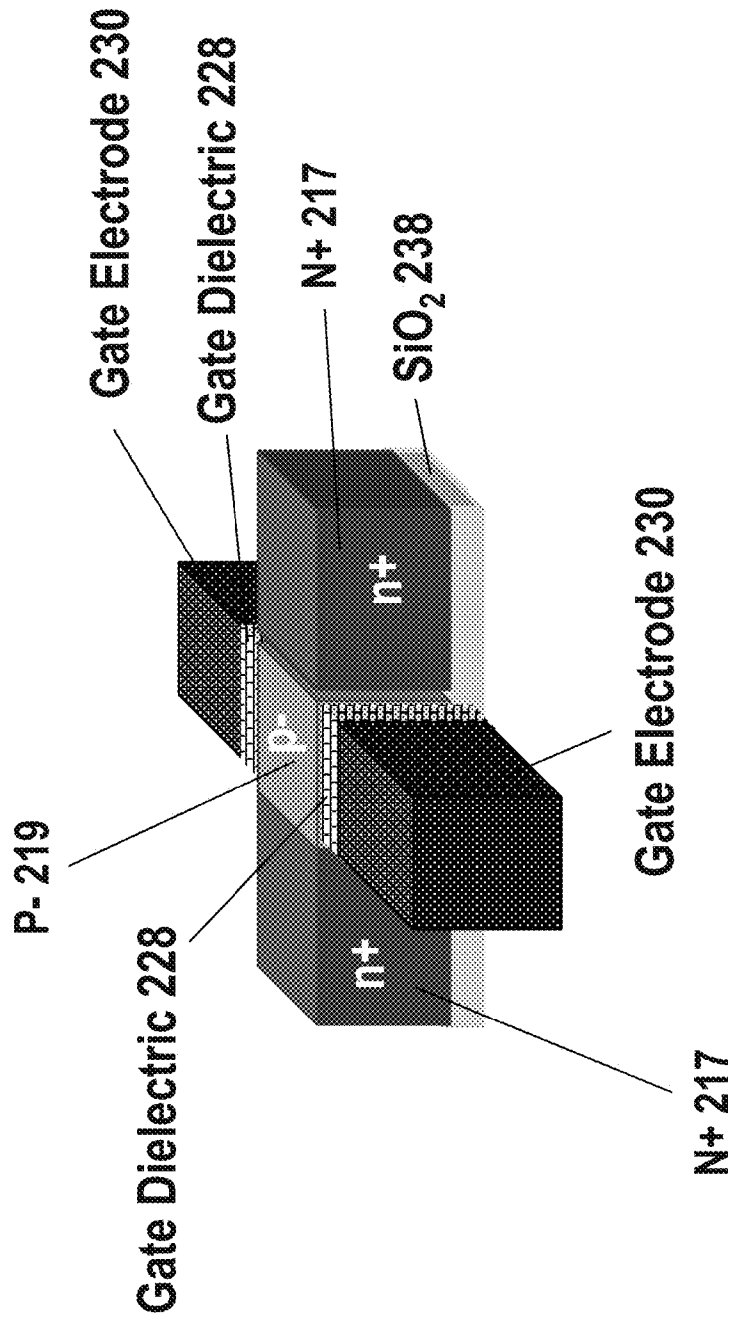


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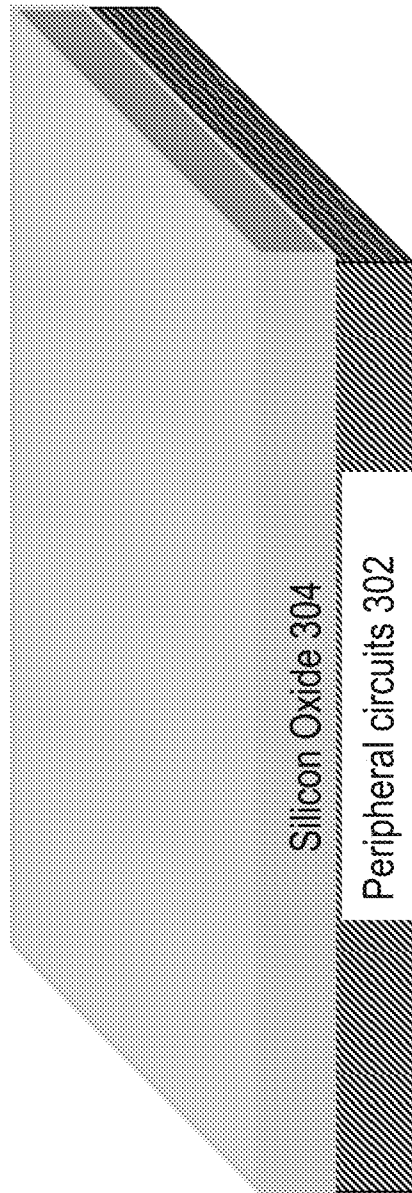


Fig. 3A

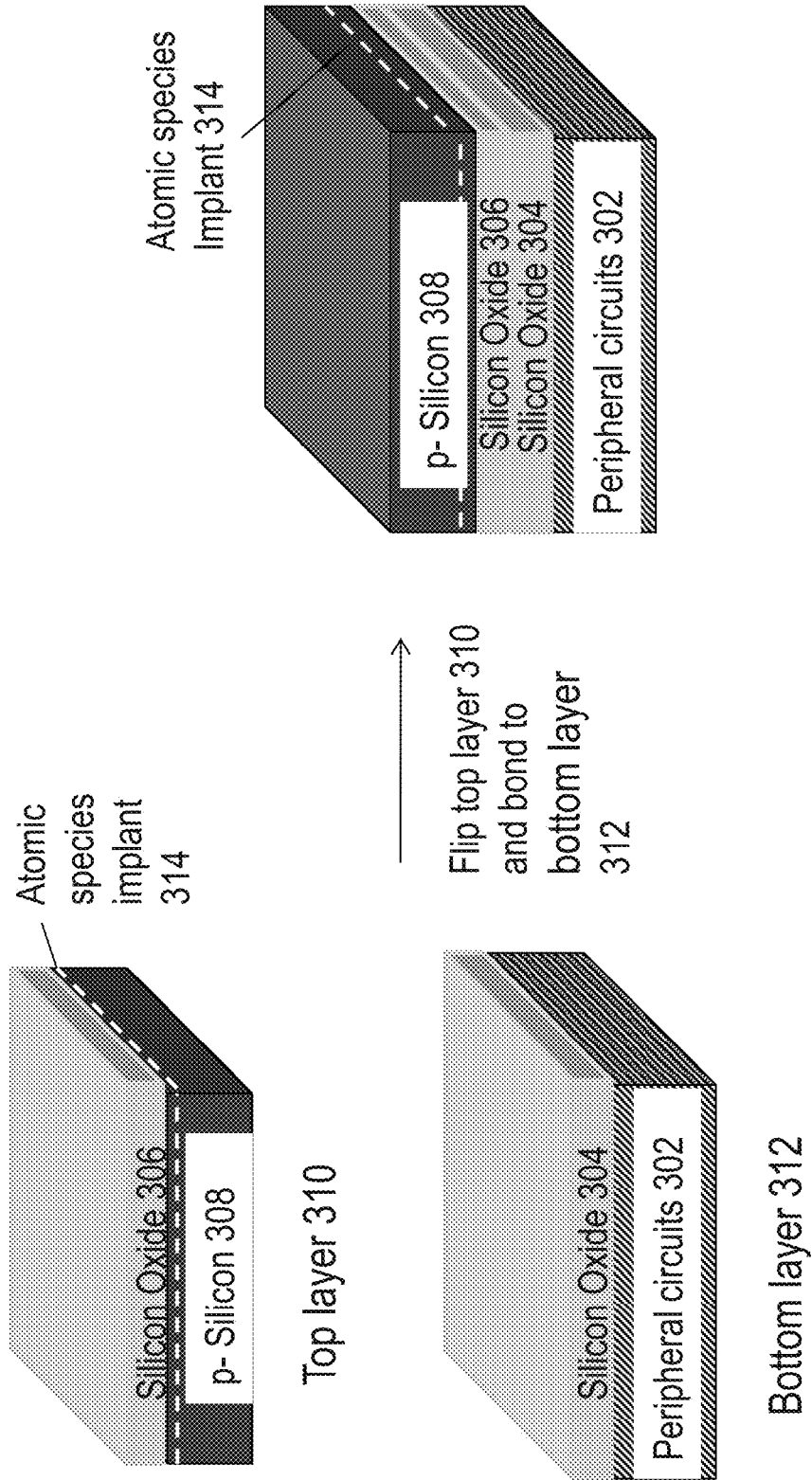


Fig. 3B

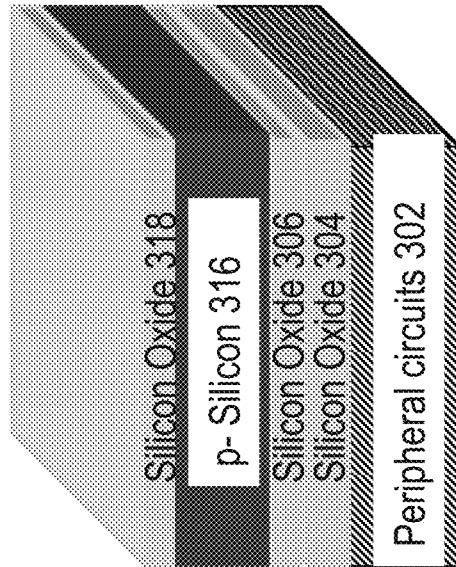


Fig. 3C

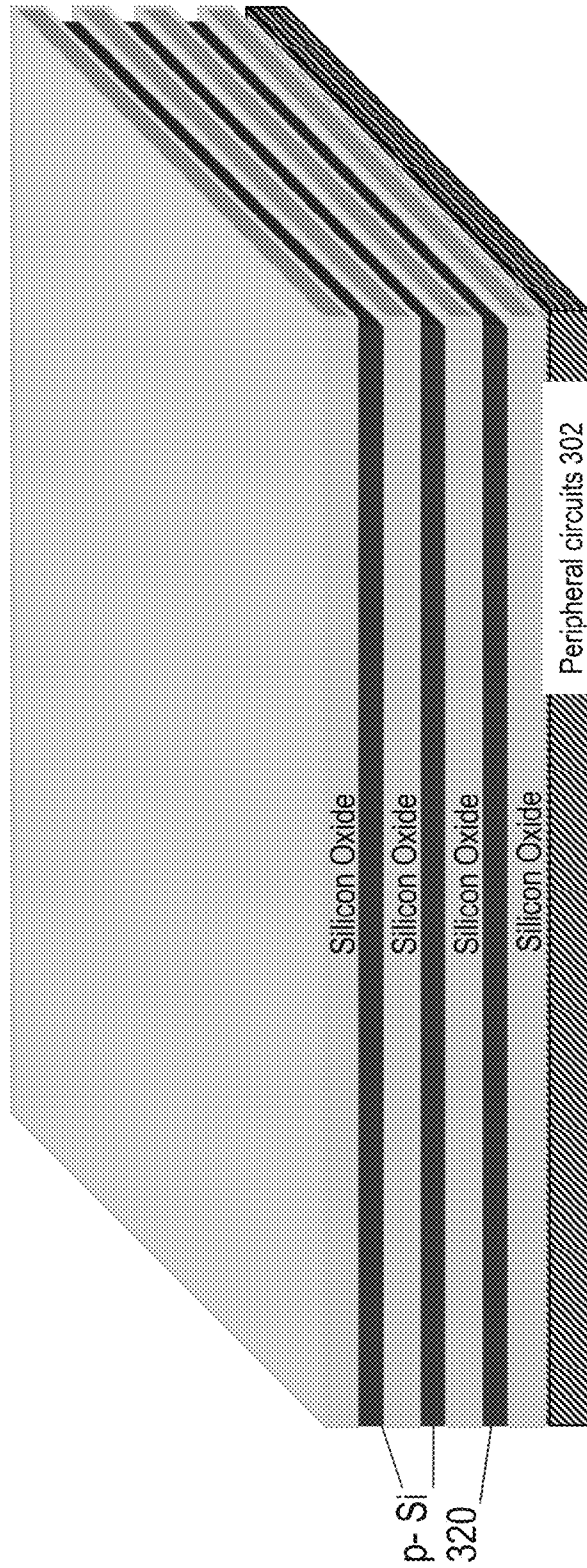
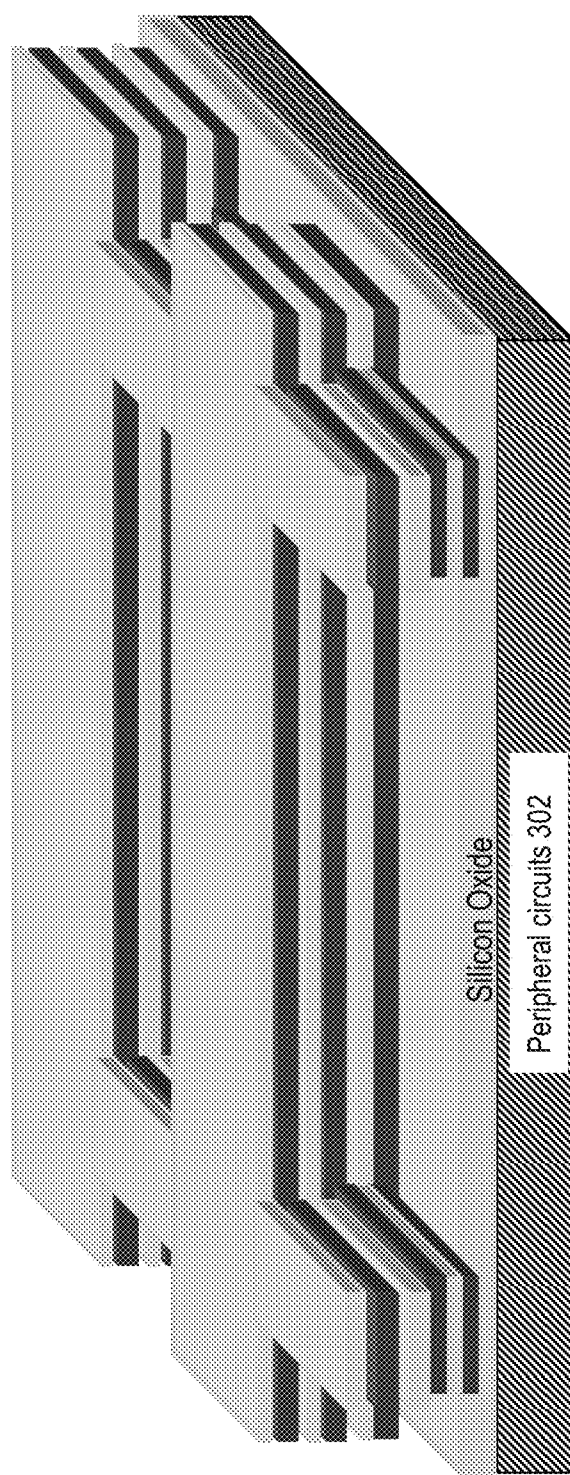


Fig. 3D



Symbols

- p- Silicon 321
- Silicon oxide 322

Fig. 3E

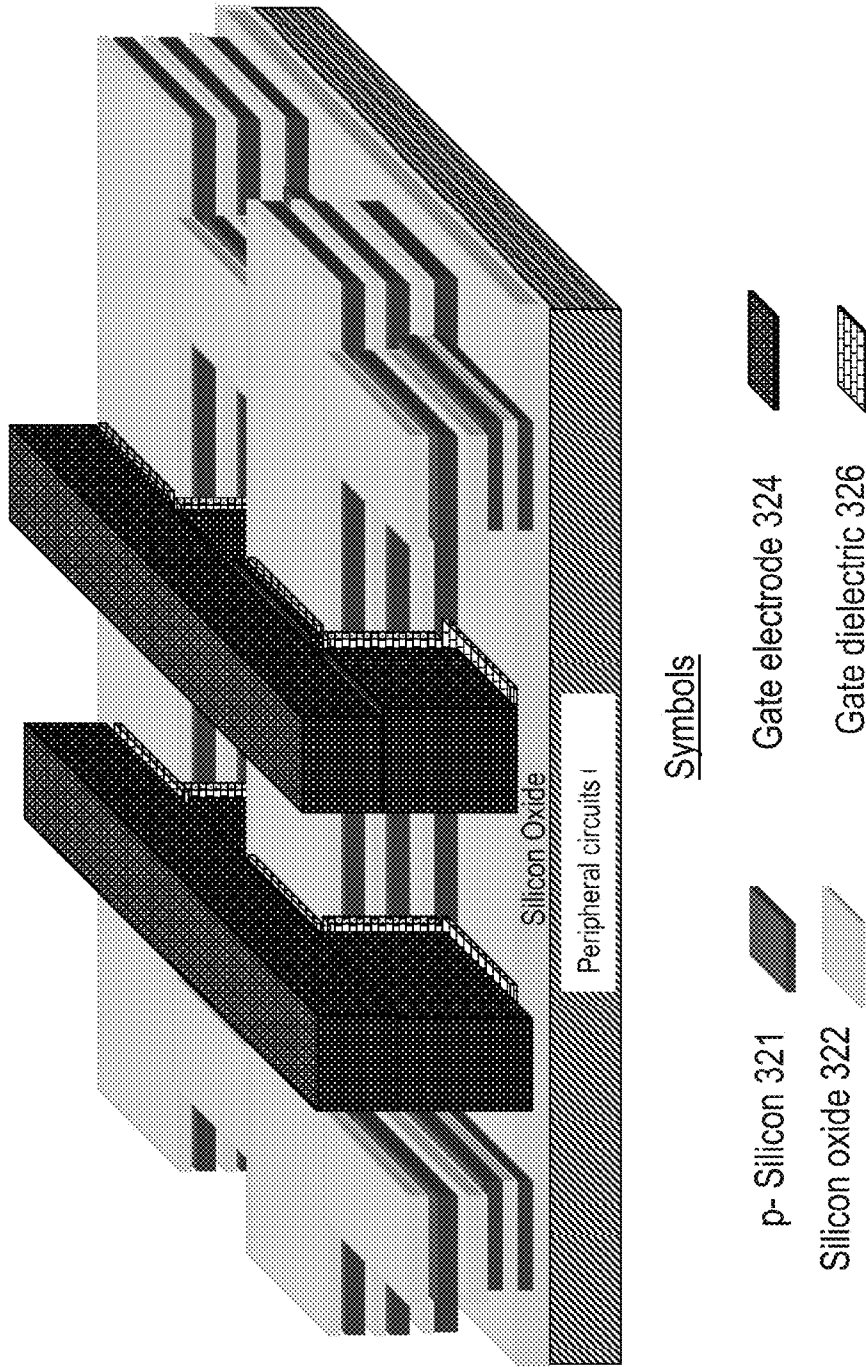


Fig. 3F

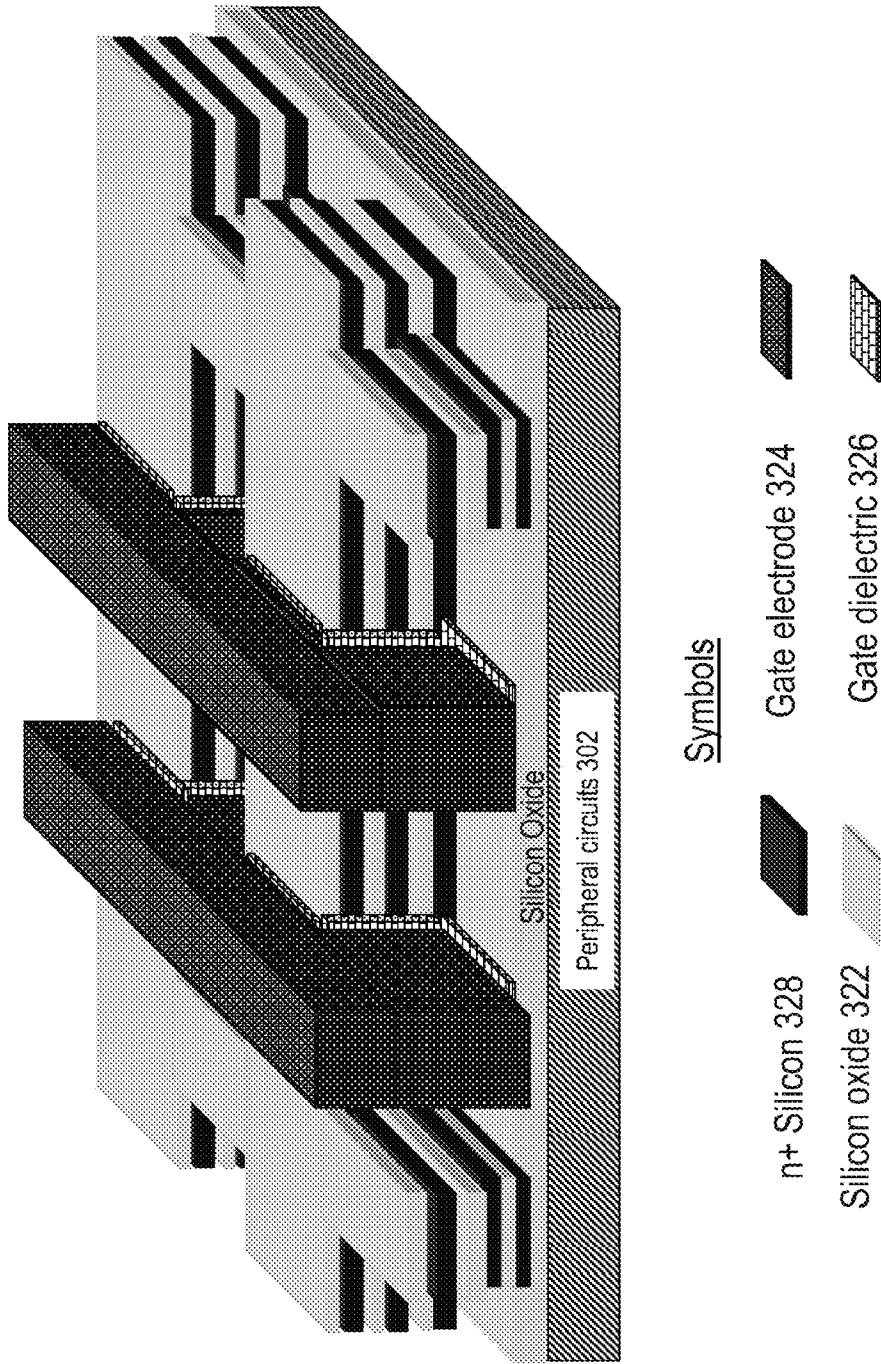


Fig. 3G

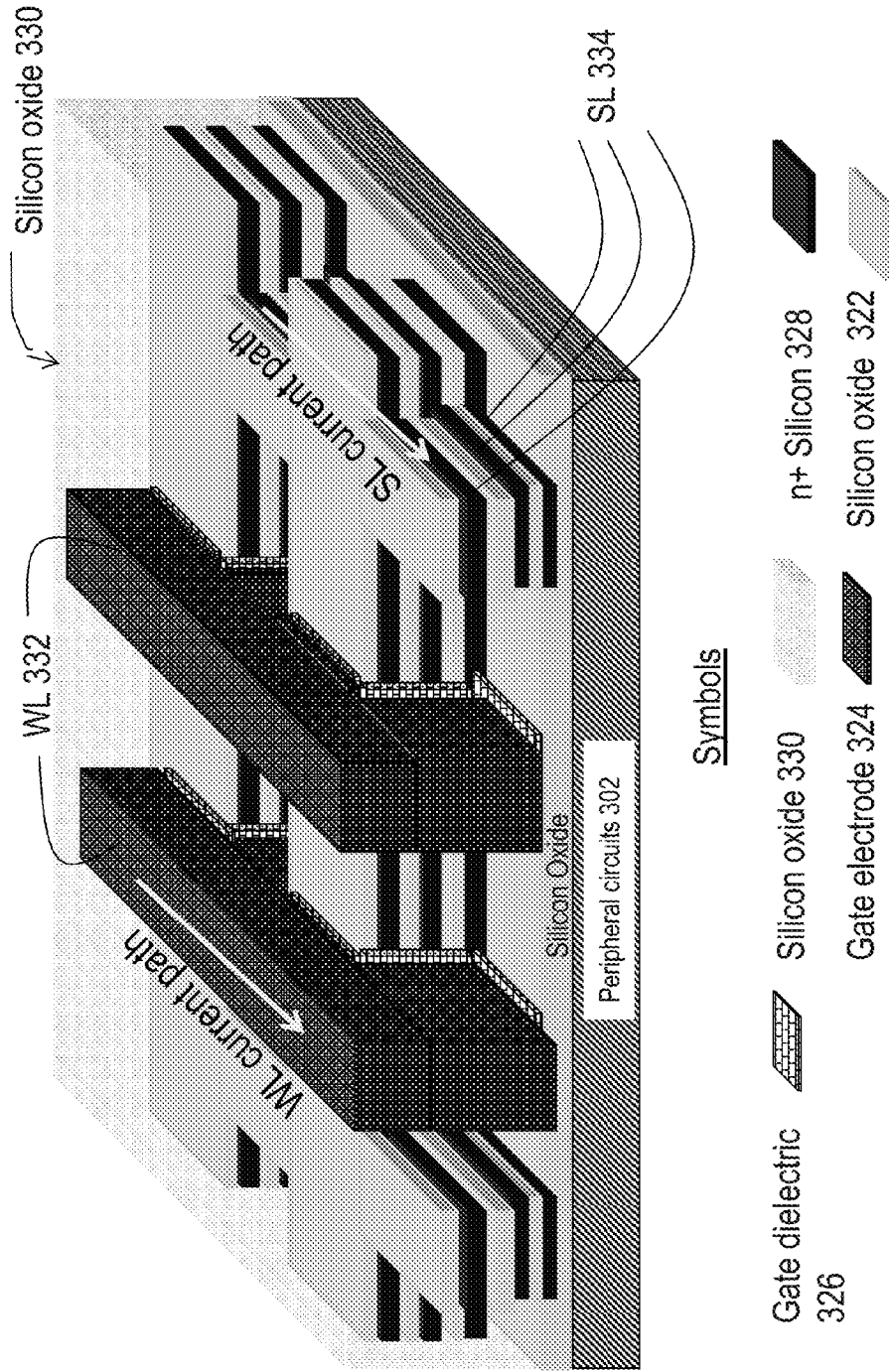


Fig. 3H

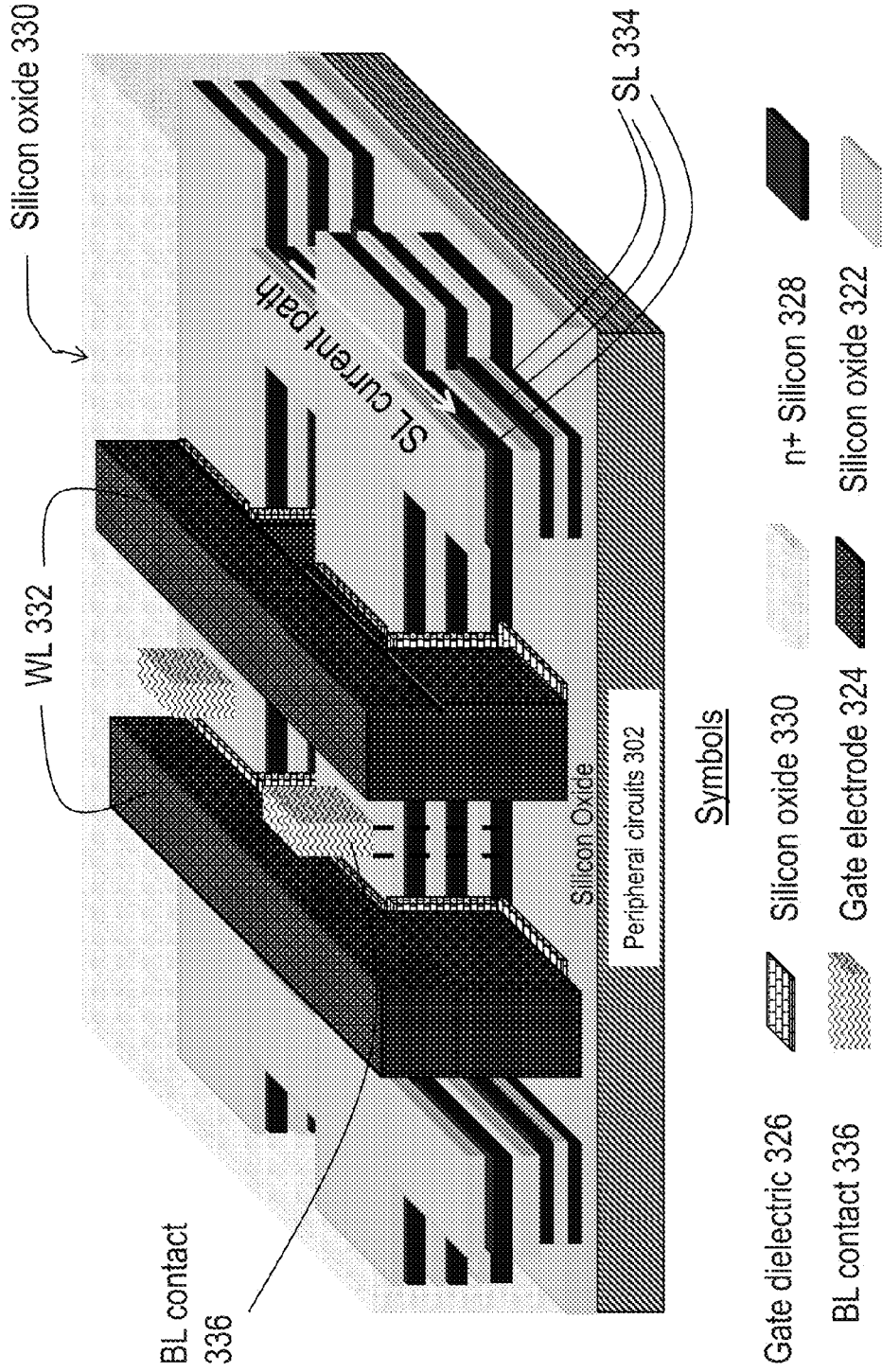


Fig. 3I

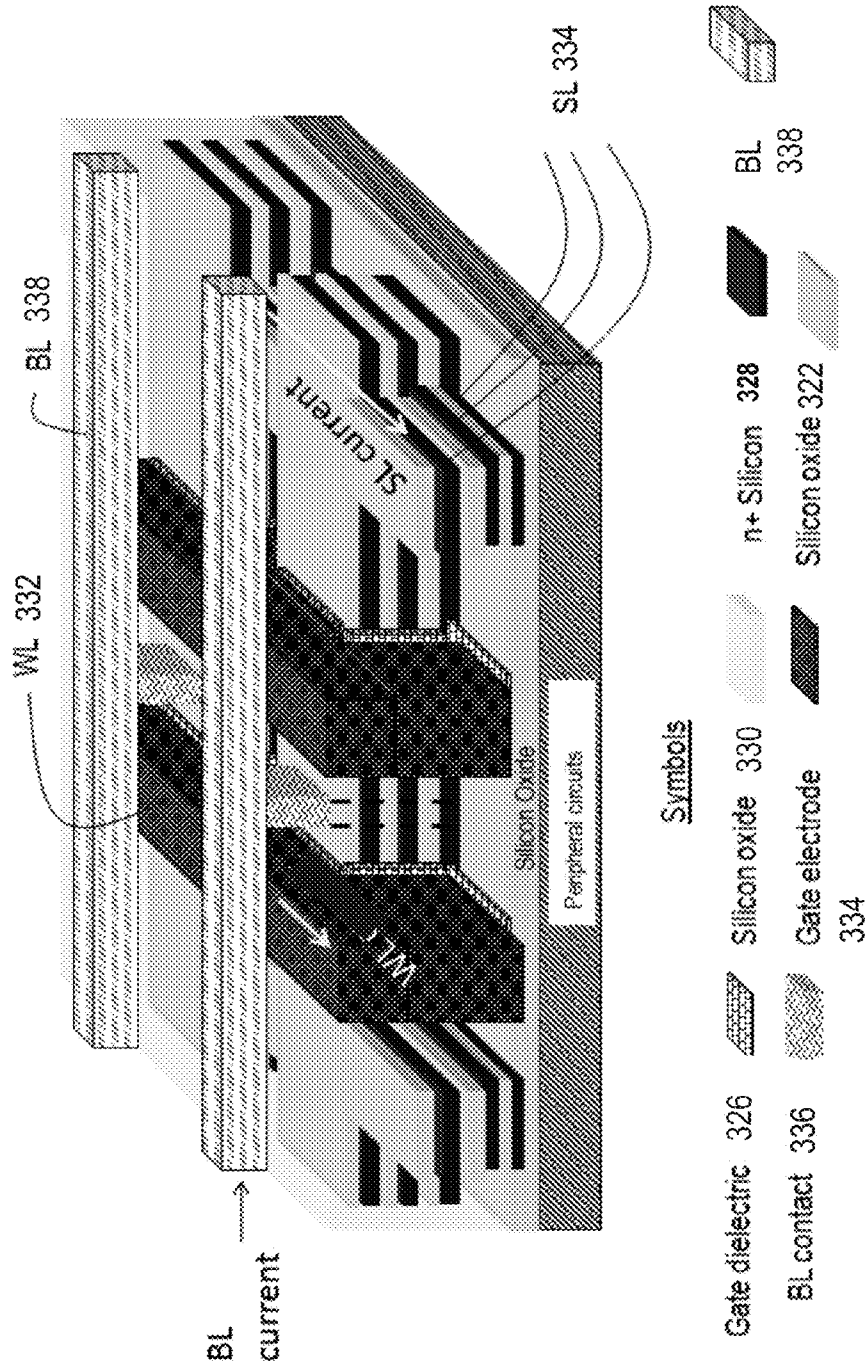


Fig. 3J

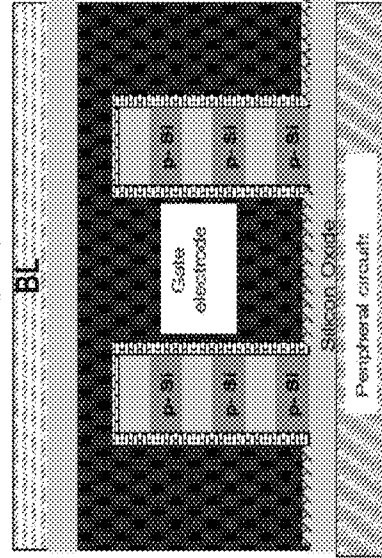
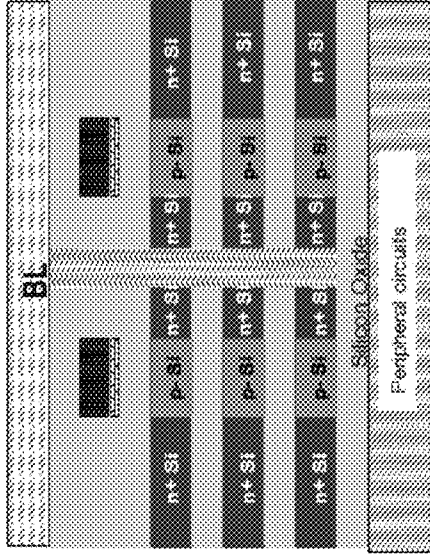
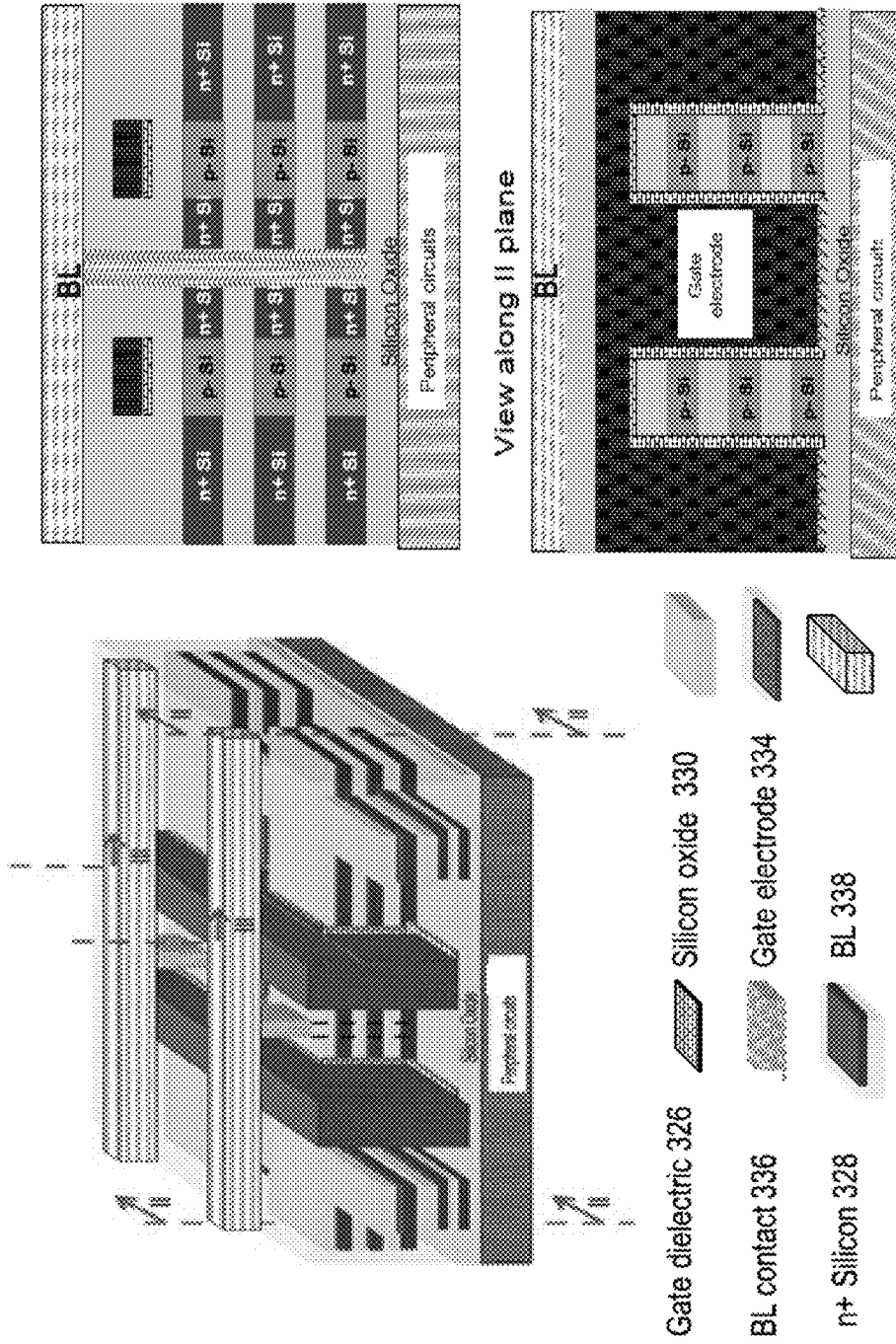


Fig. 3K

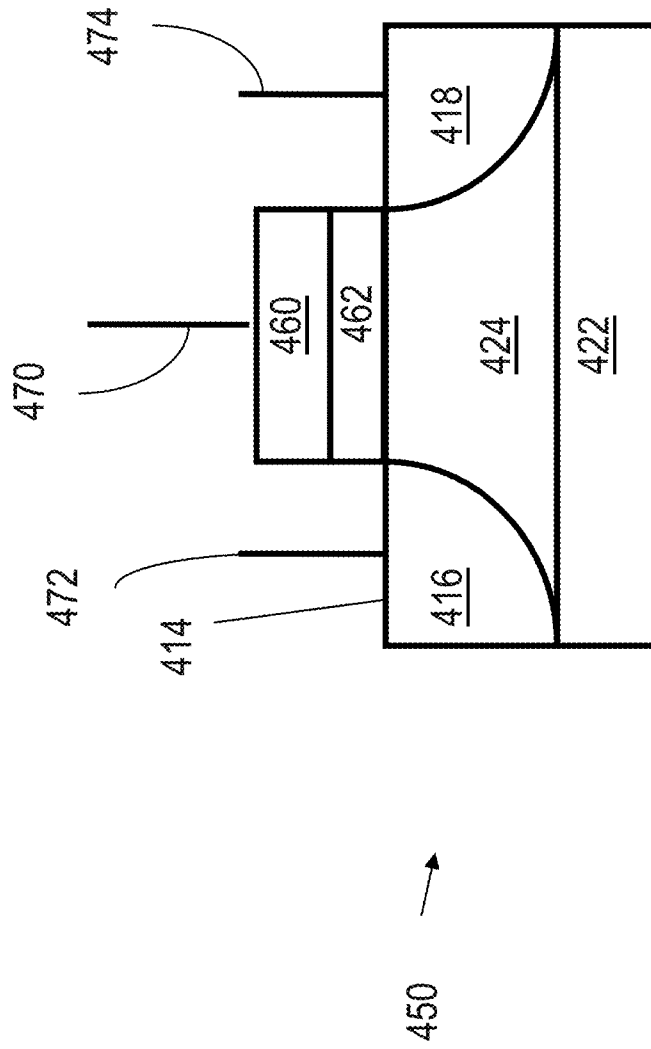


Fig. 4A

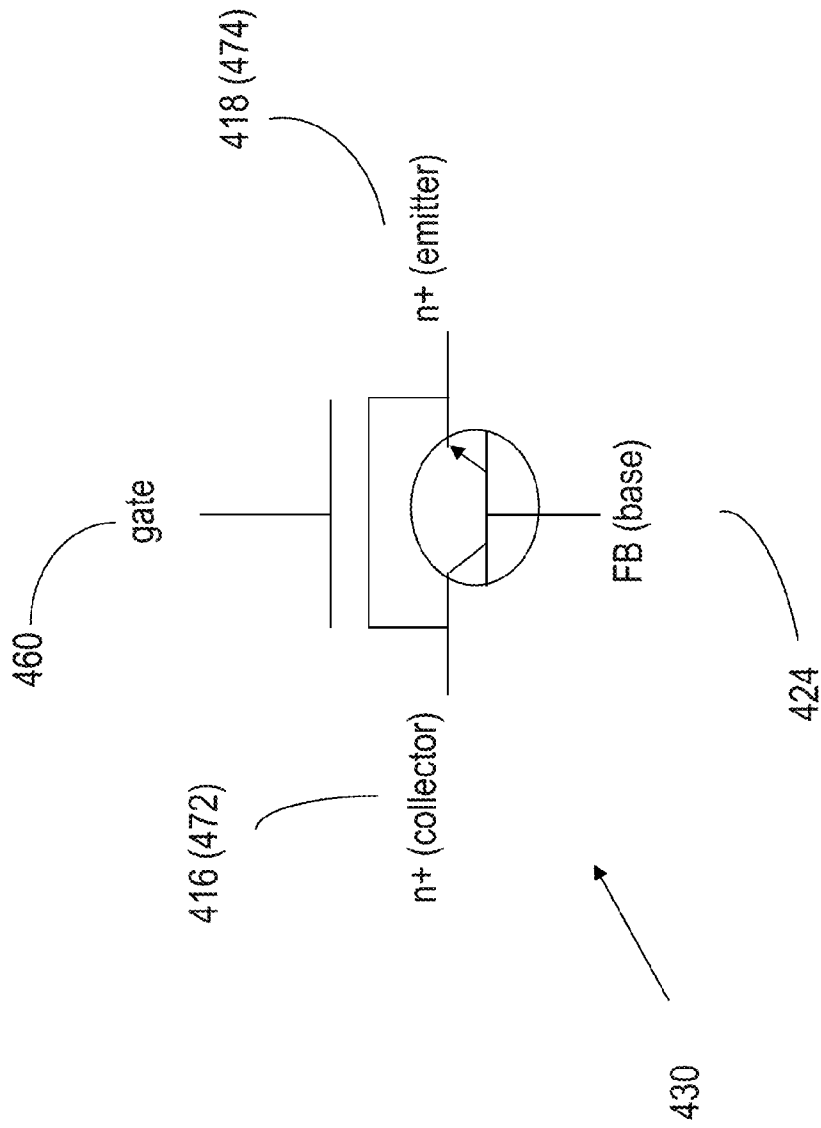


Fig. 4B

Floating Body 424 is positively charged and $V(\text{emitter}) = 0.0V$

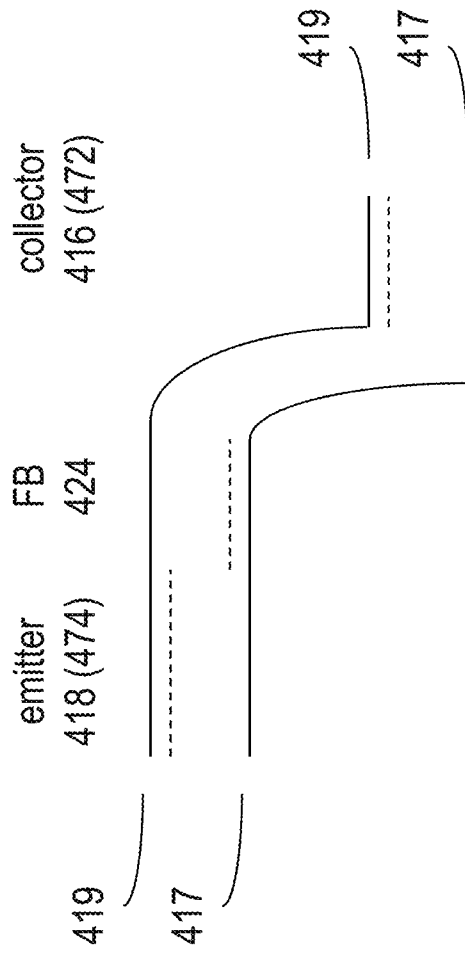


Fig. 4C

FB is neutrally charged: and $V(\text{emitter}) = V(\text{FB } 424) = 0V$

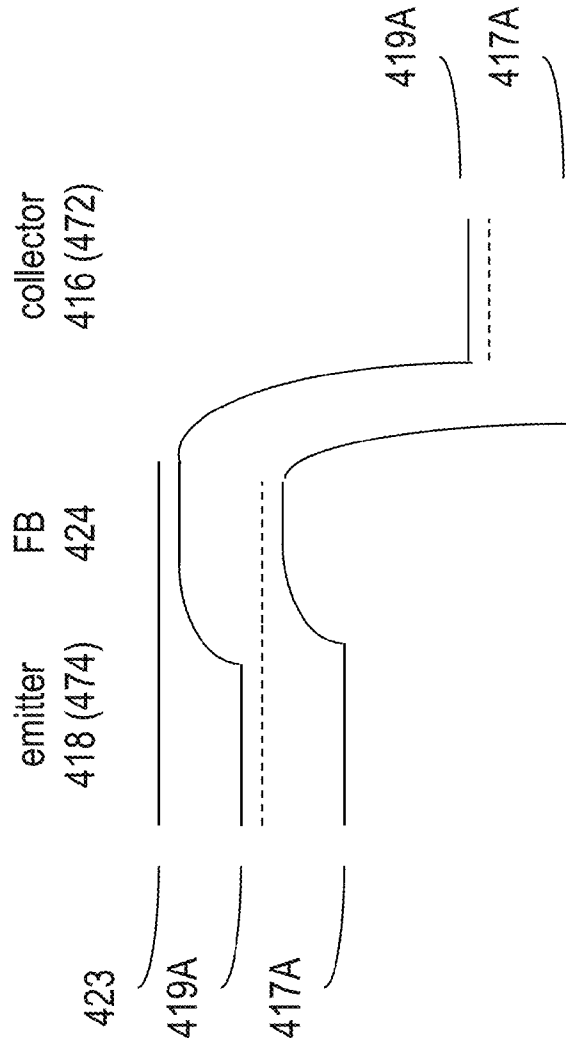


Fig. 4D

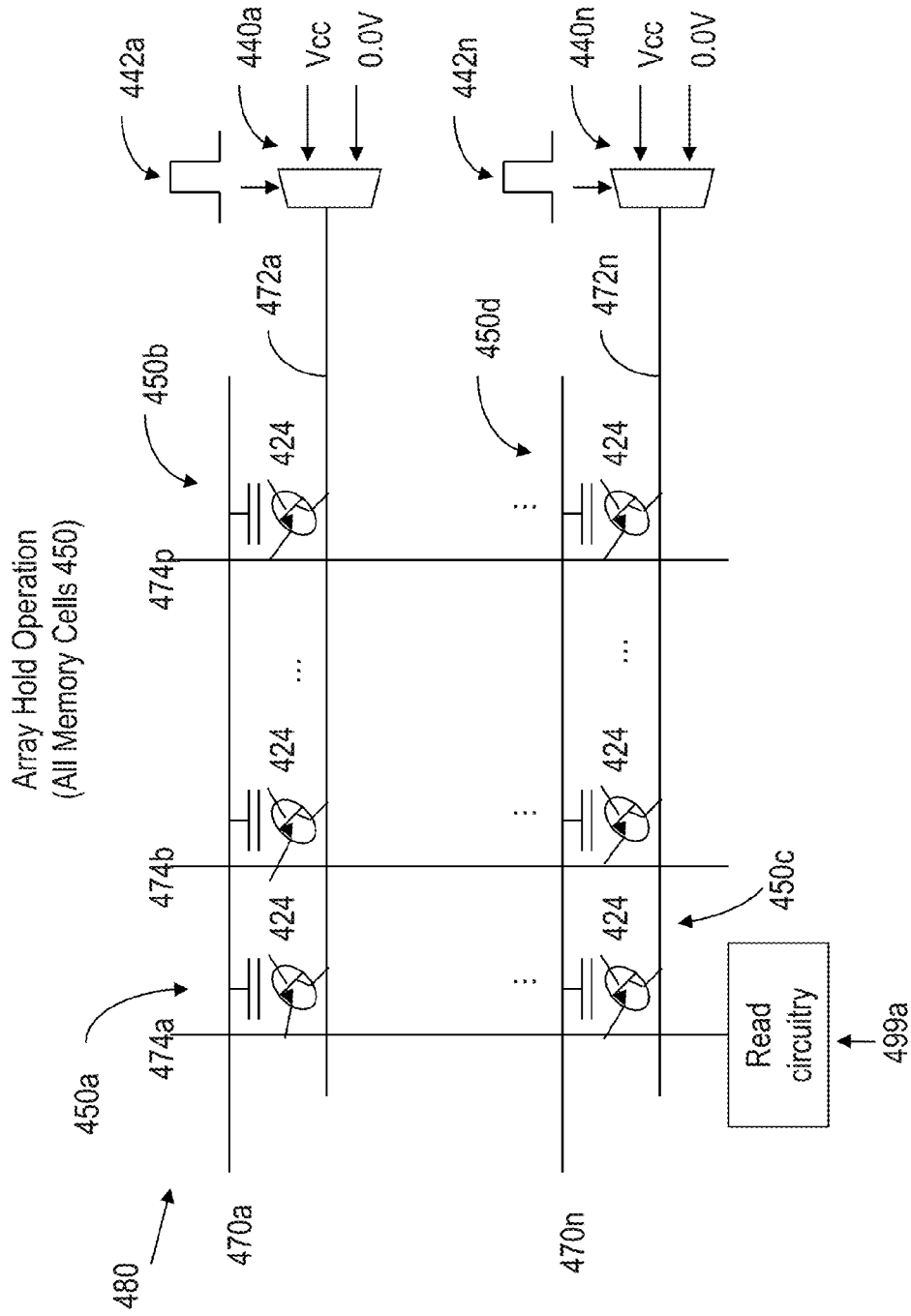


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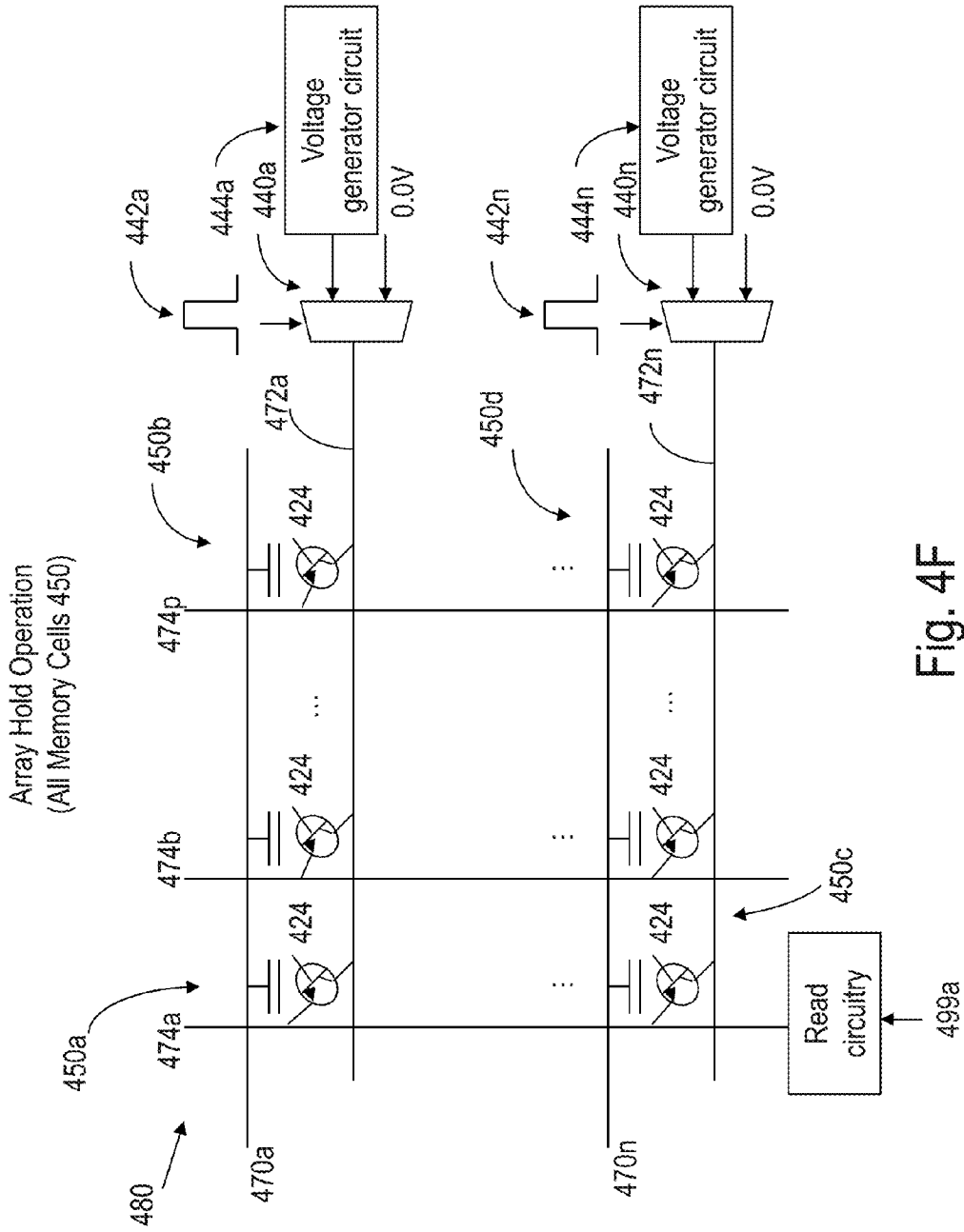


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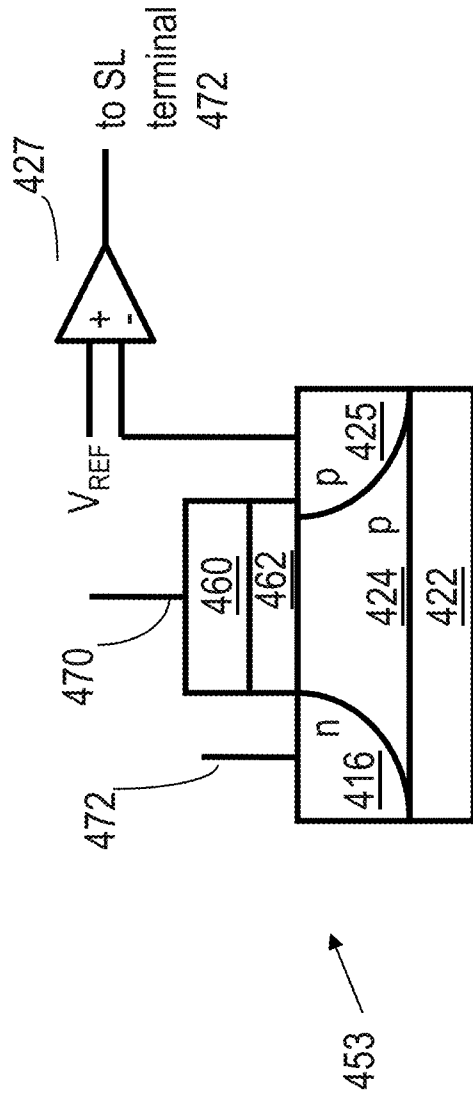


Fig. 4G

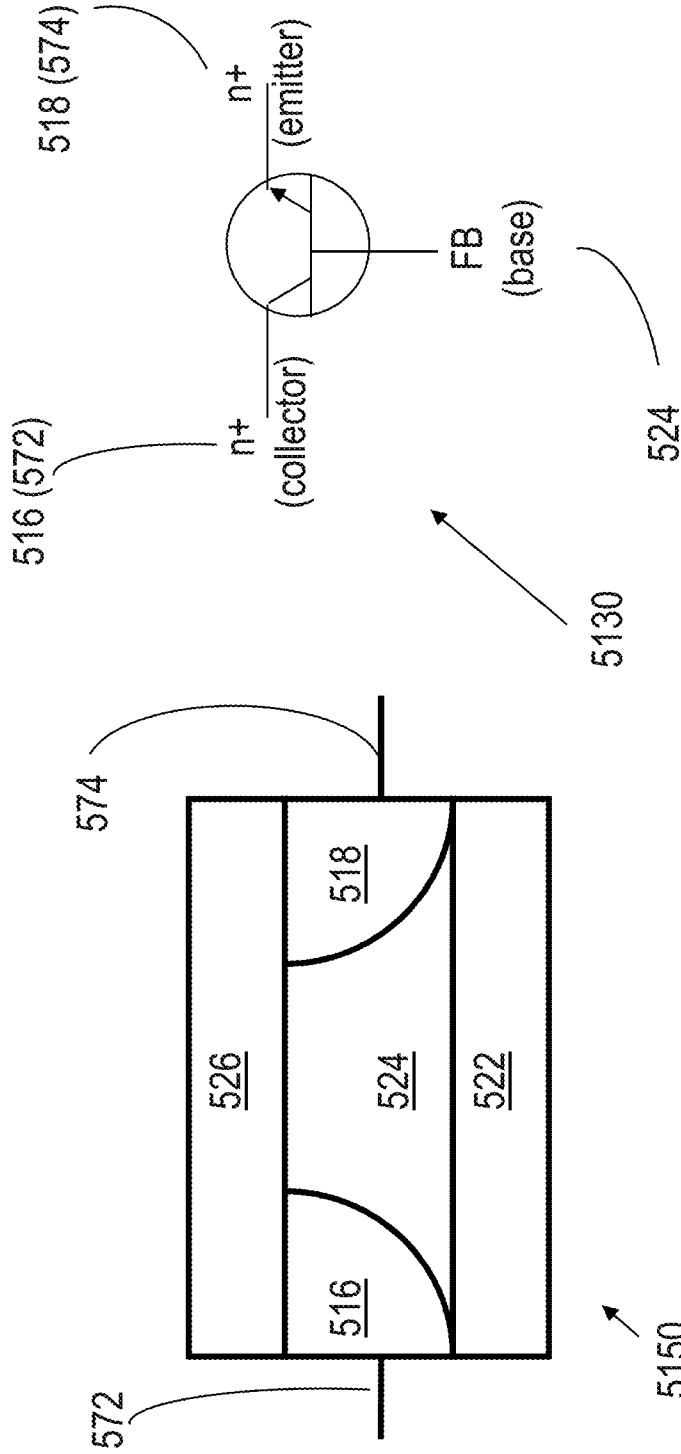


Fig. 5B

Fig. 5A

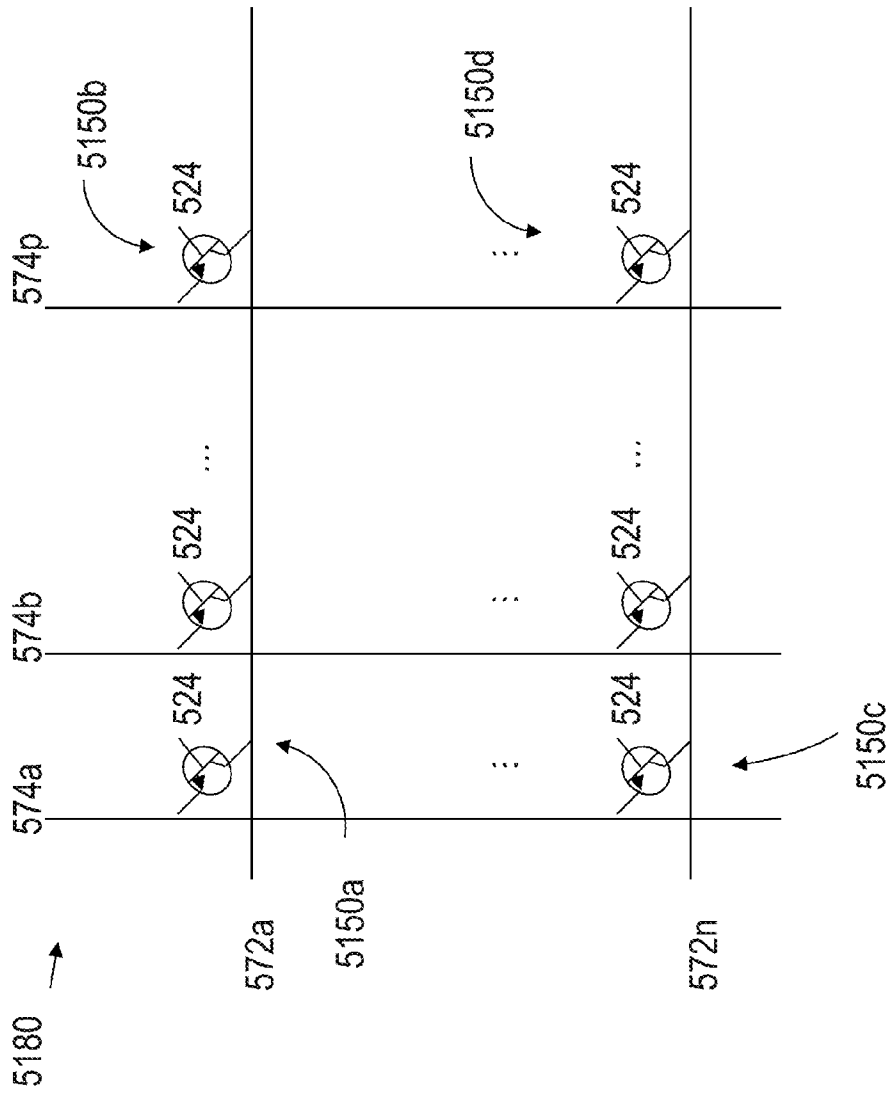


Fig. 5C

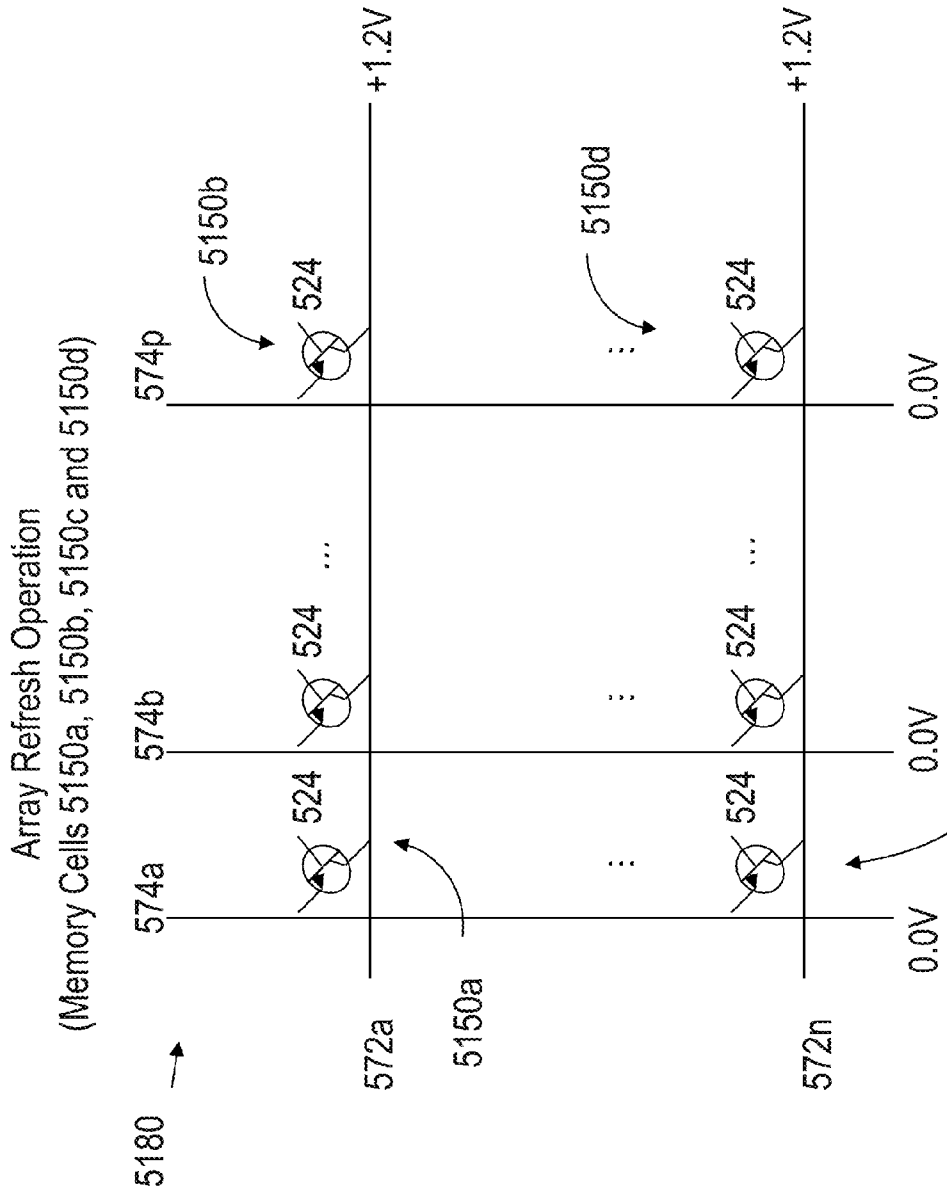


Fig. 5D

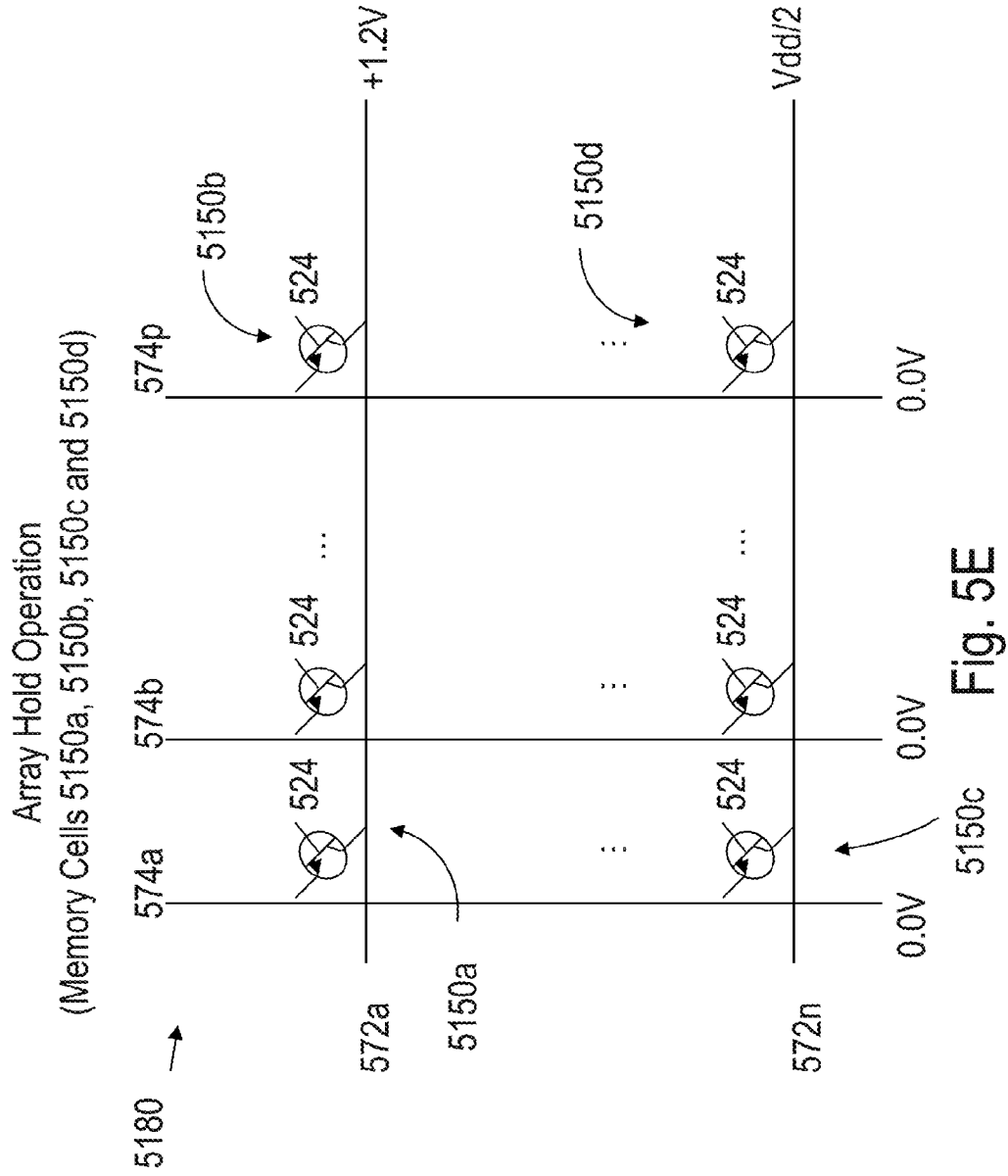


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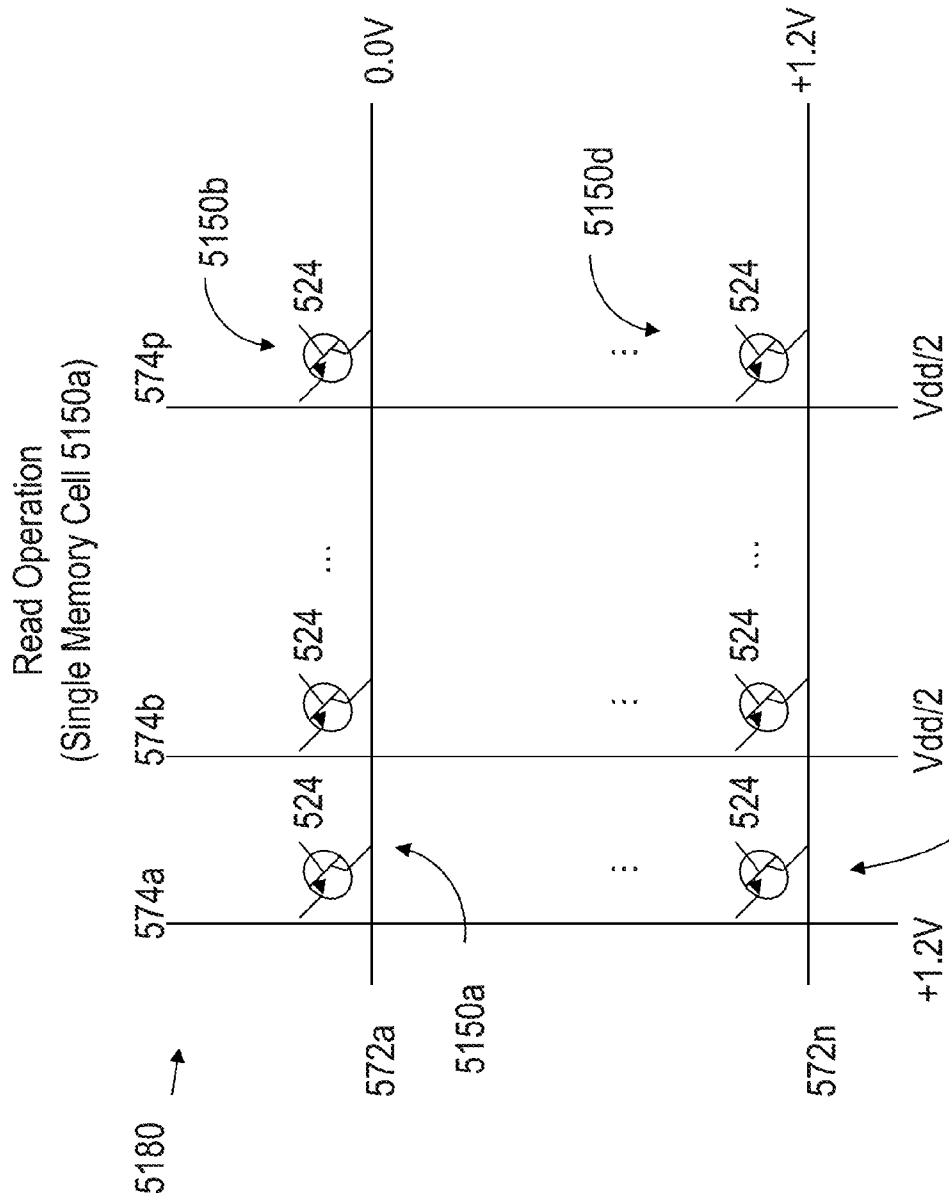
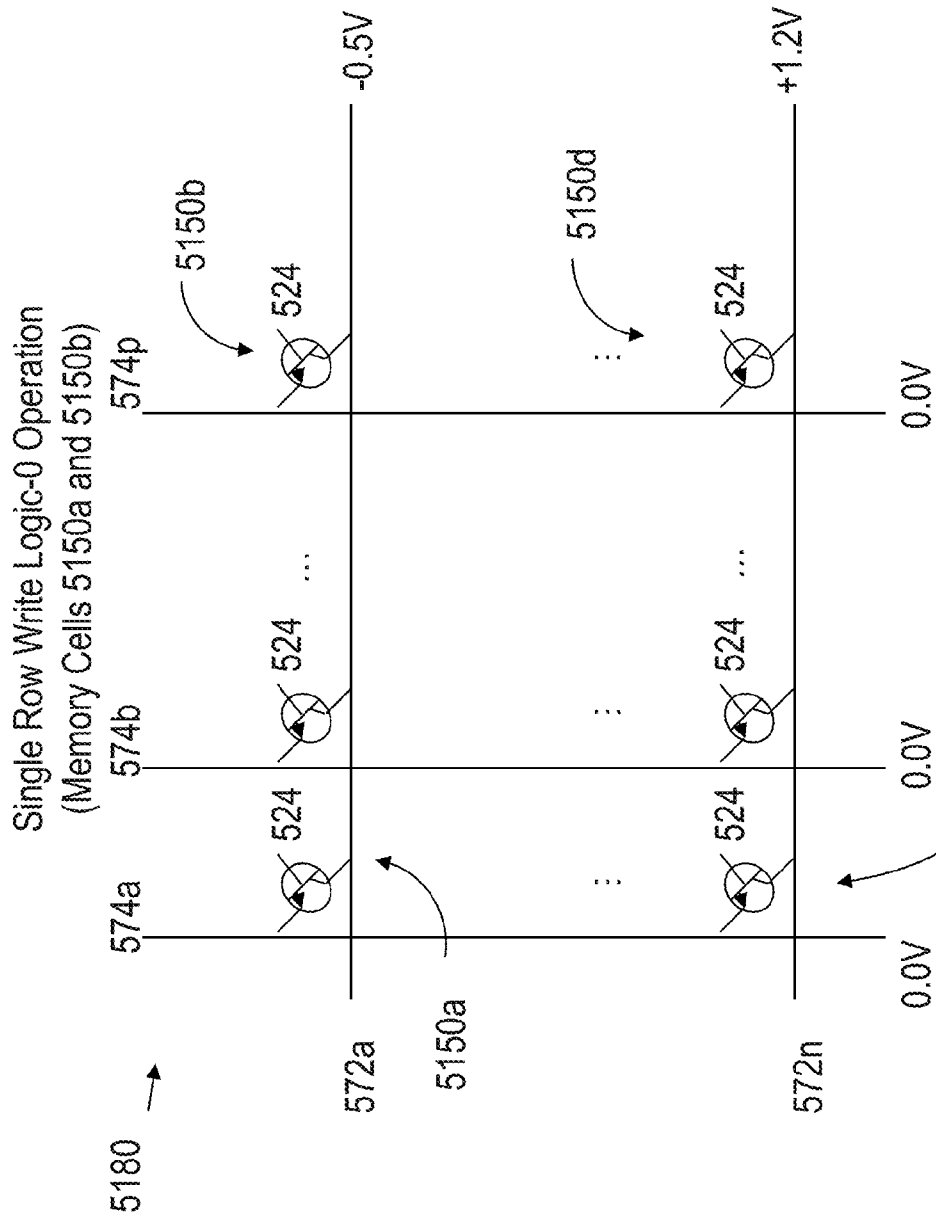
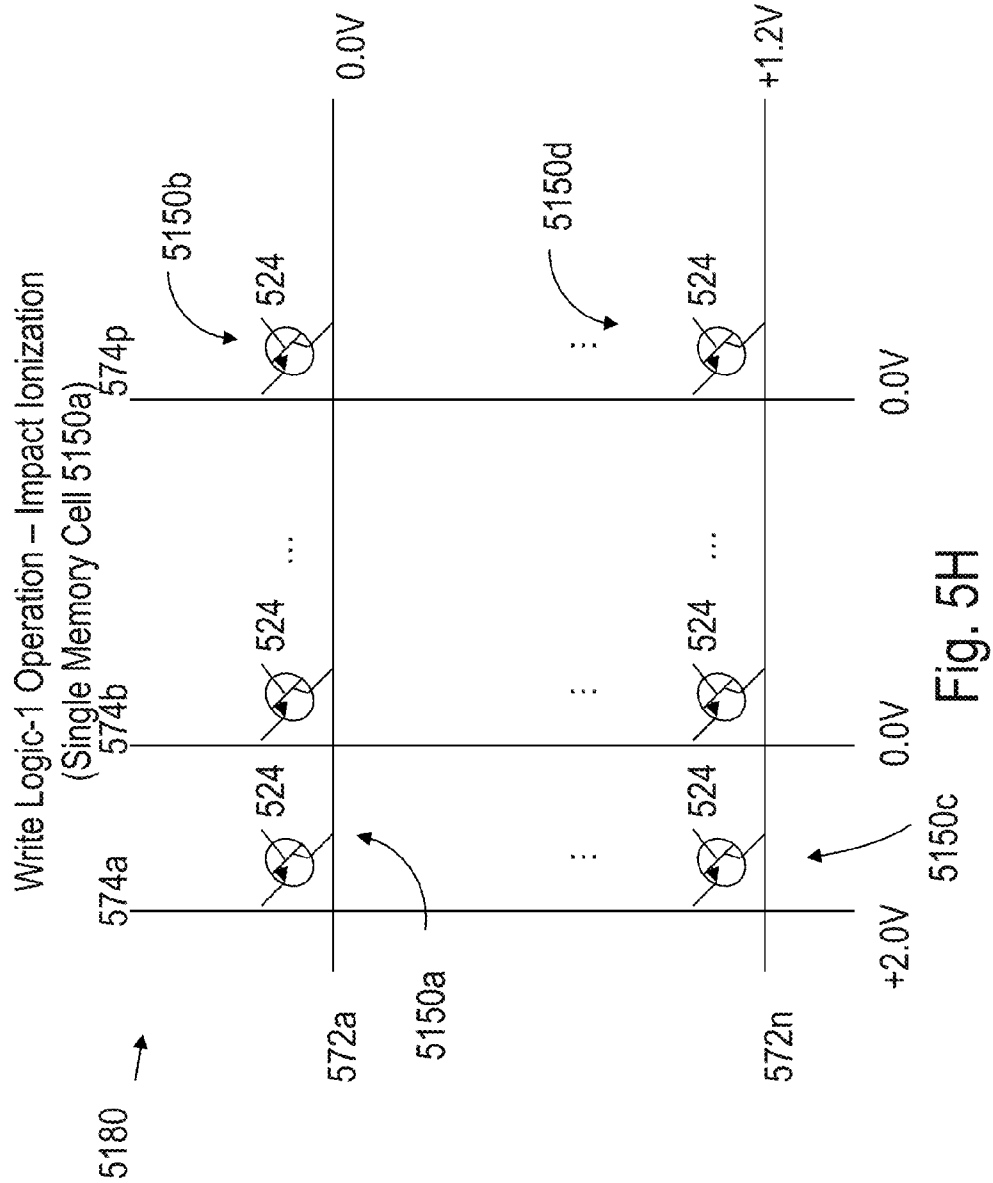


Fig. 5F

5150c



5150c Fig. 5G



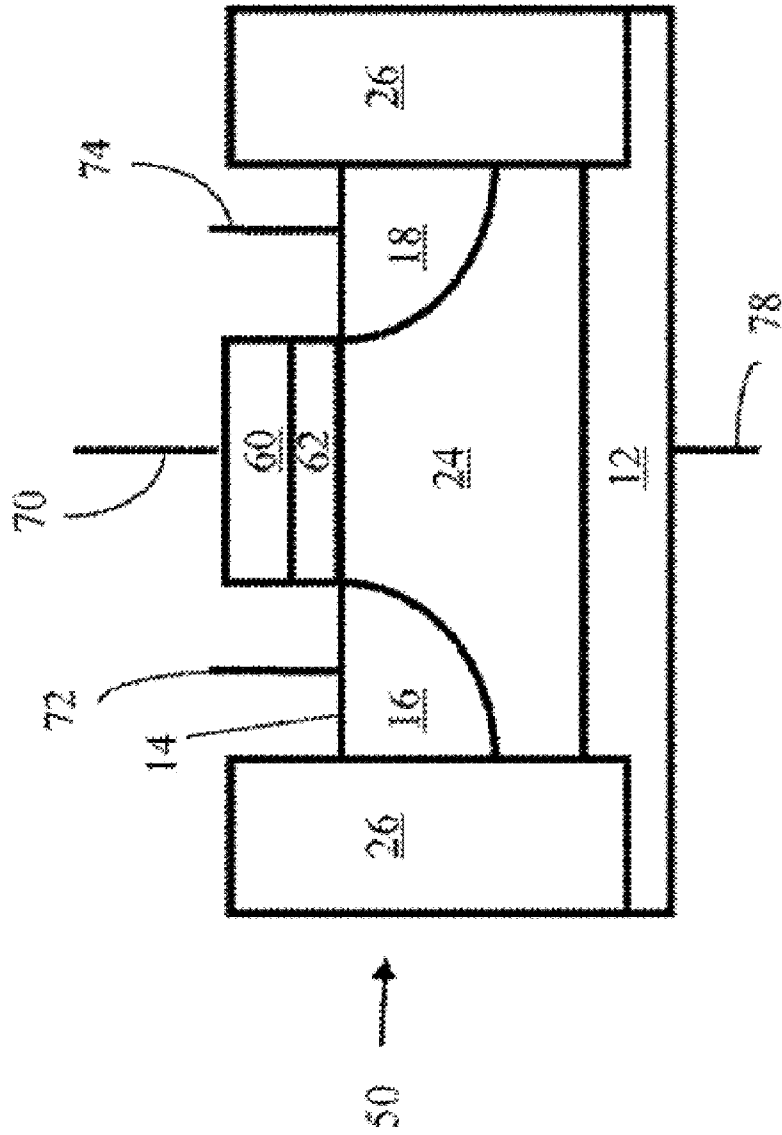


Fig. 6

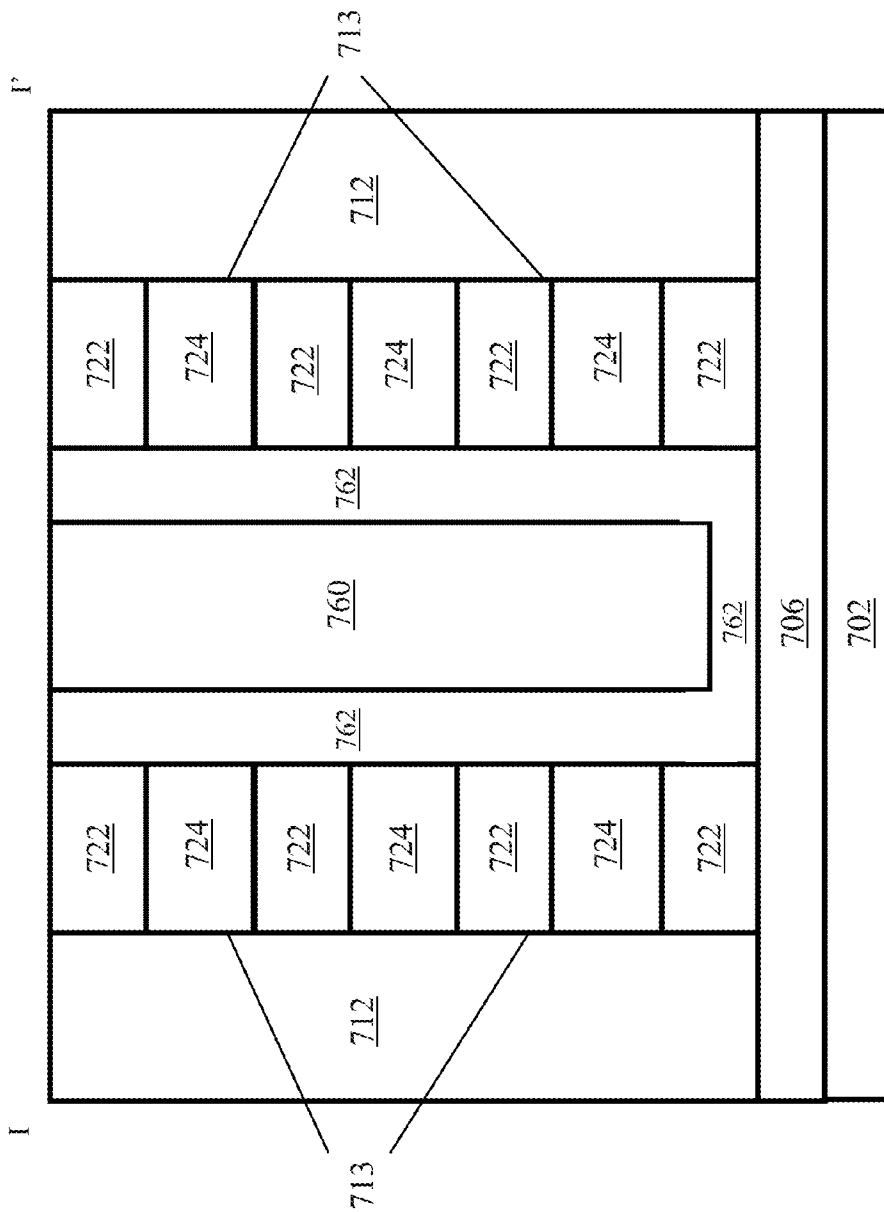


Fig. 7B – Cross Sectional View I of Fig. 7A

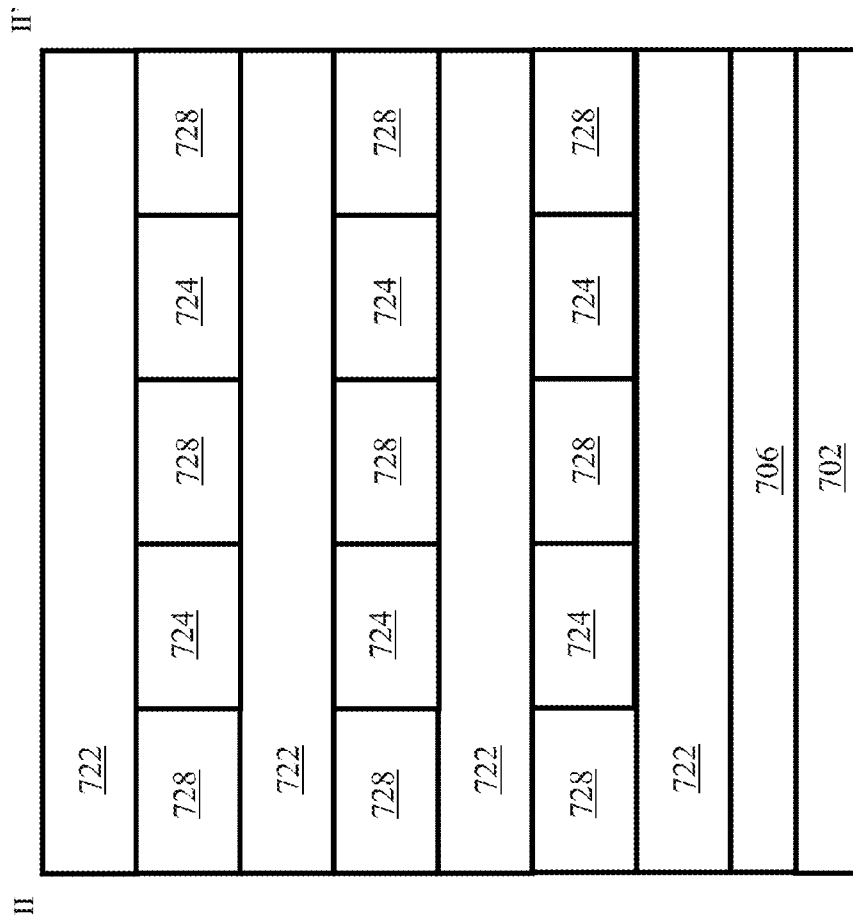


Fig. 7C – Cross Sectional View II of Fig. 7A

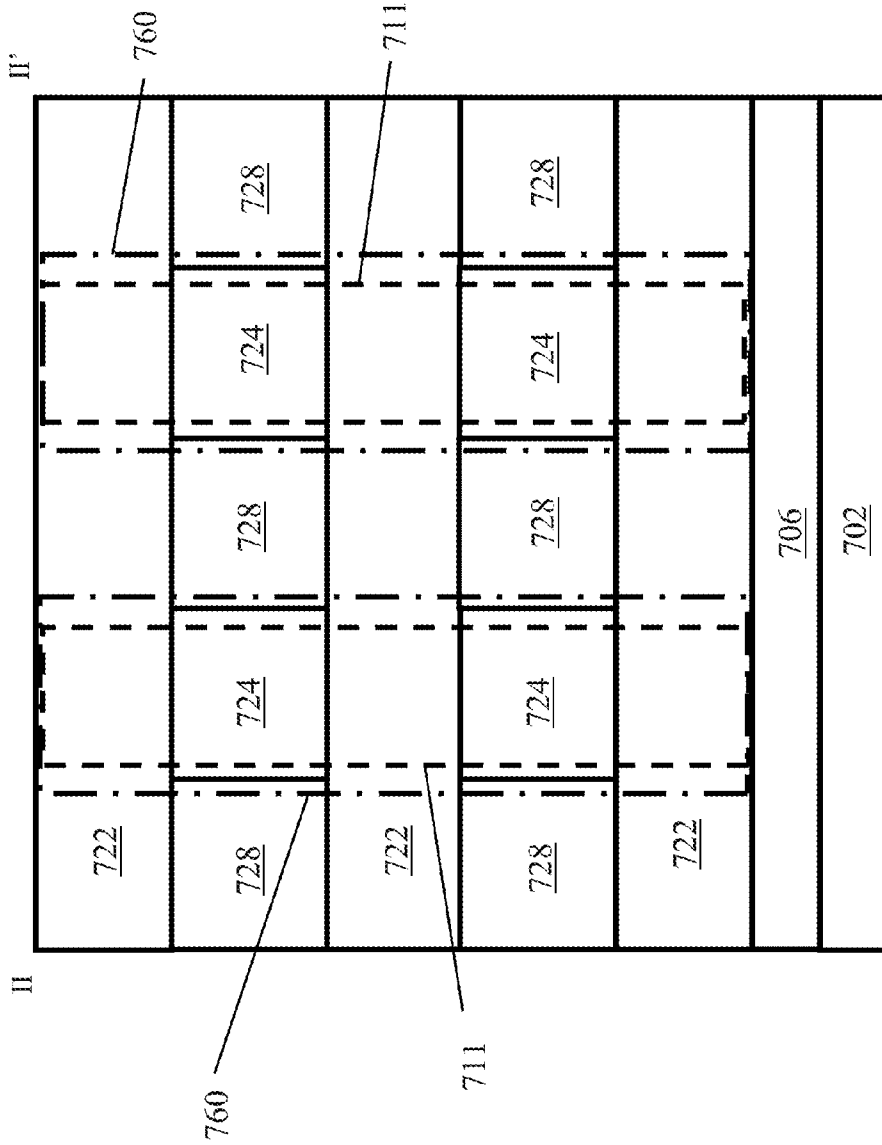


Fig. 7D – Cross Sectional View II of Fig. 7A, shadowed regions

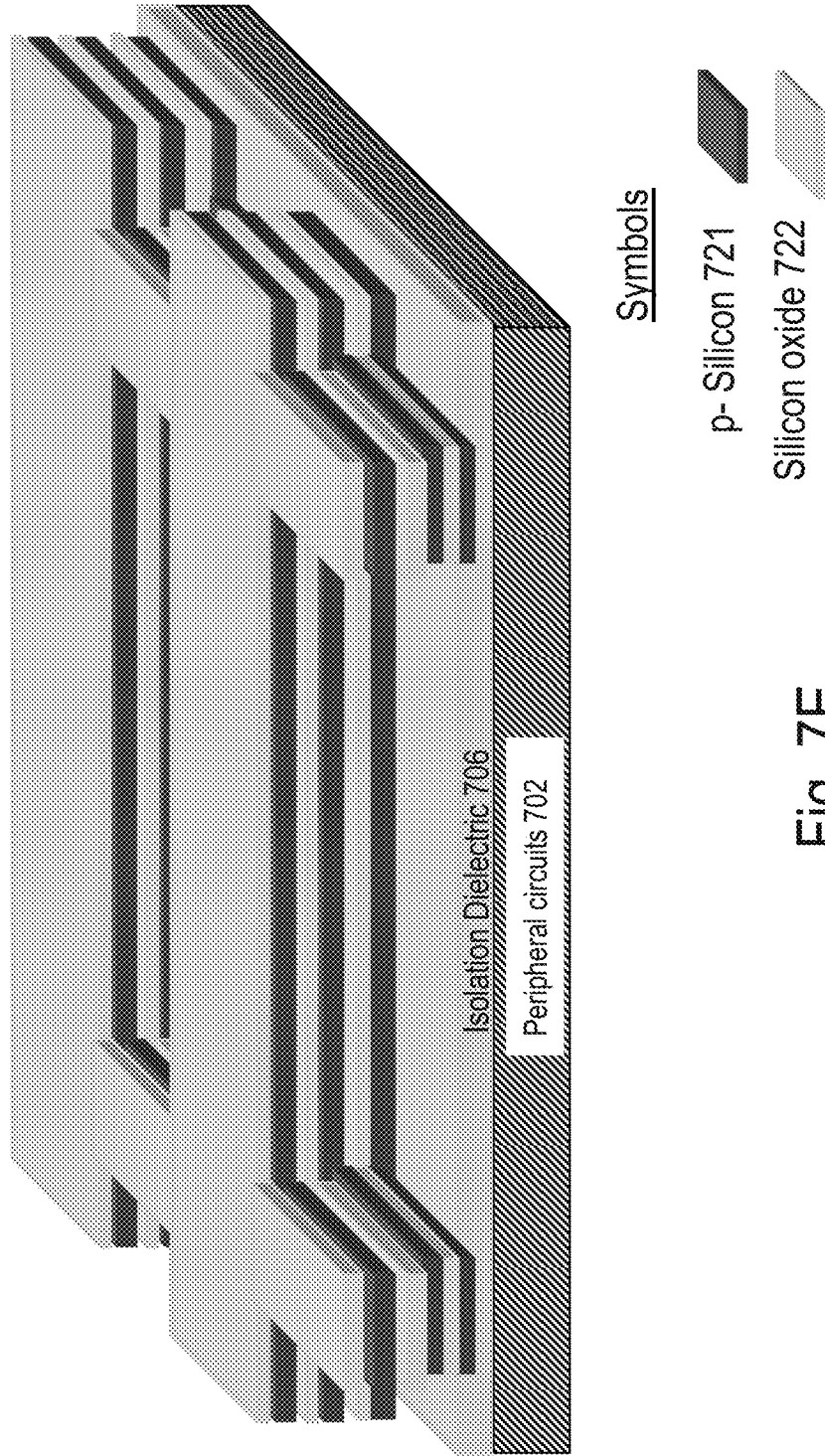


Fig. 7E

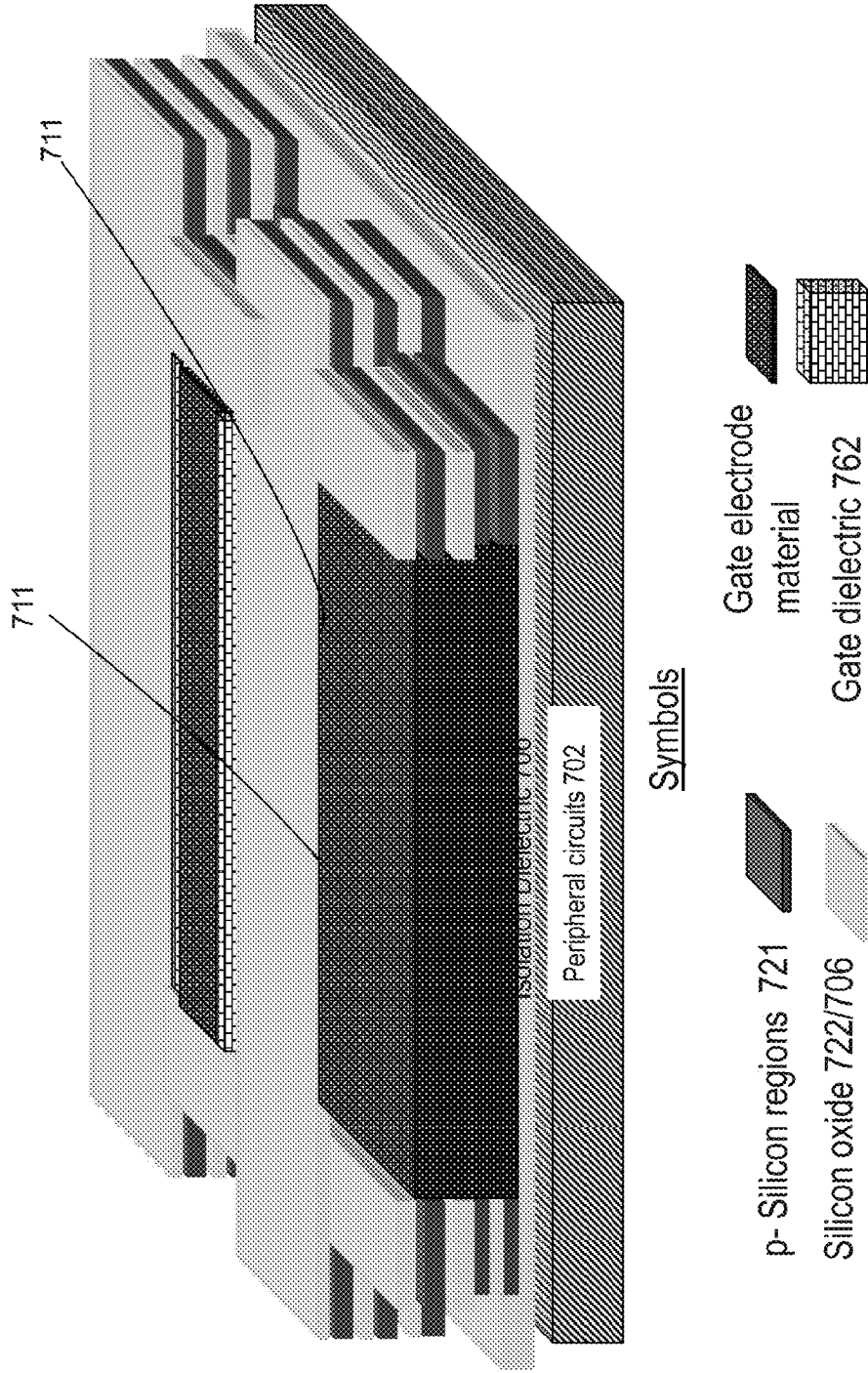


Fig. 7F

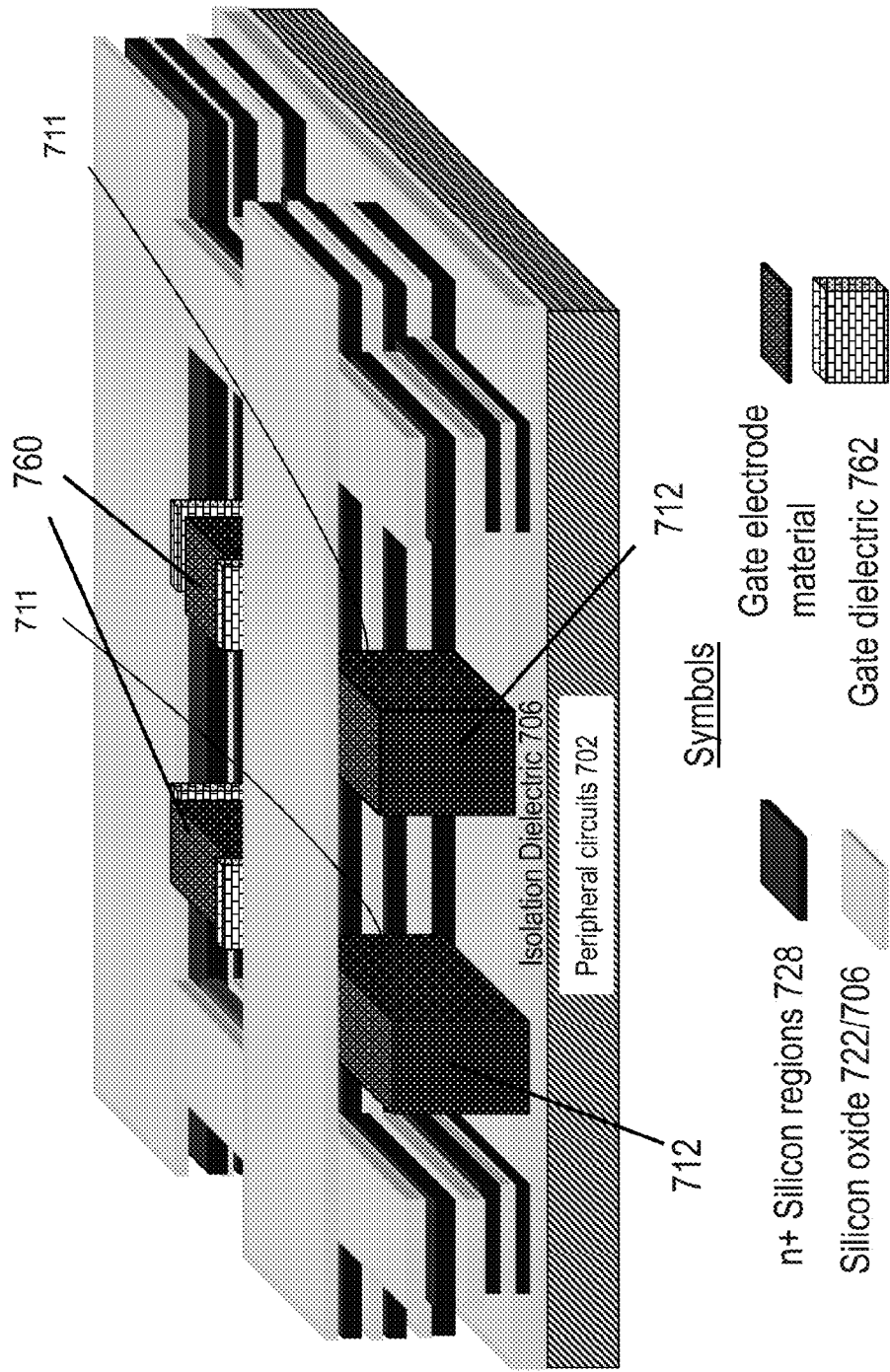


Fig. 7G

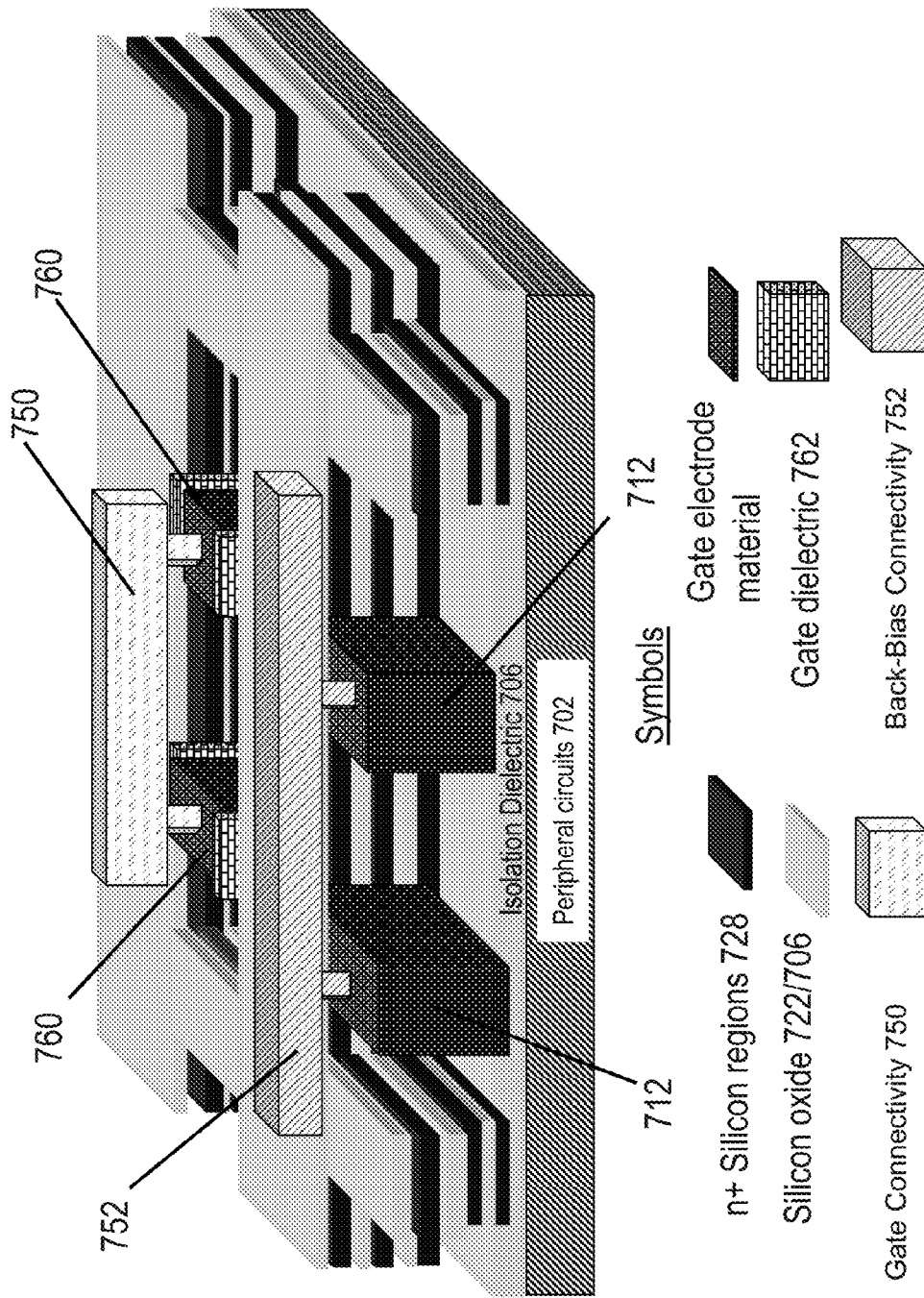


Fig. 7H

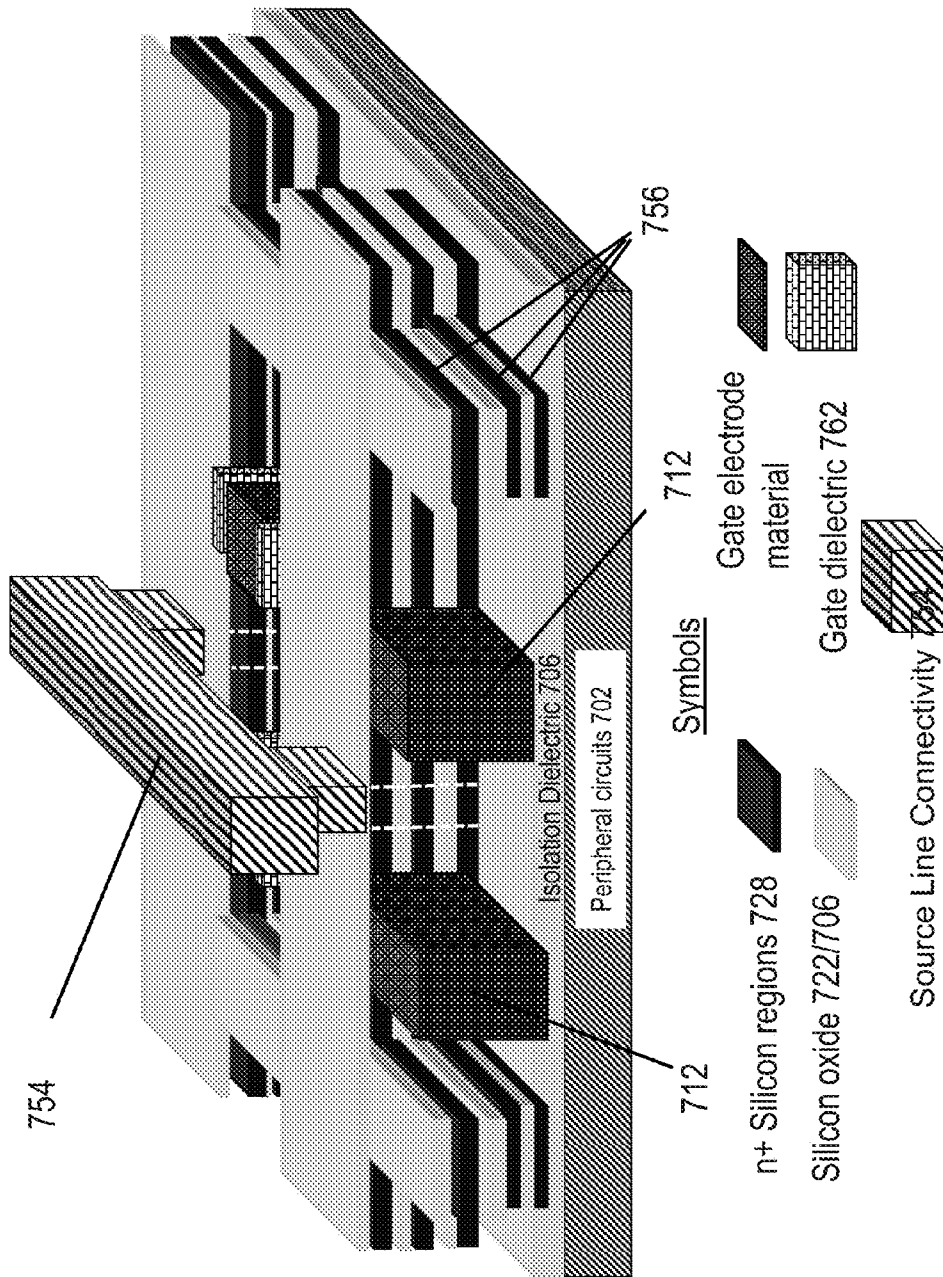


Fig. 71

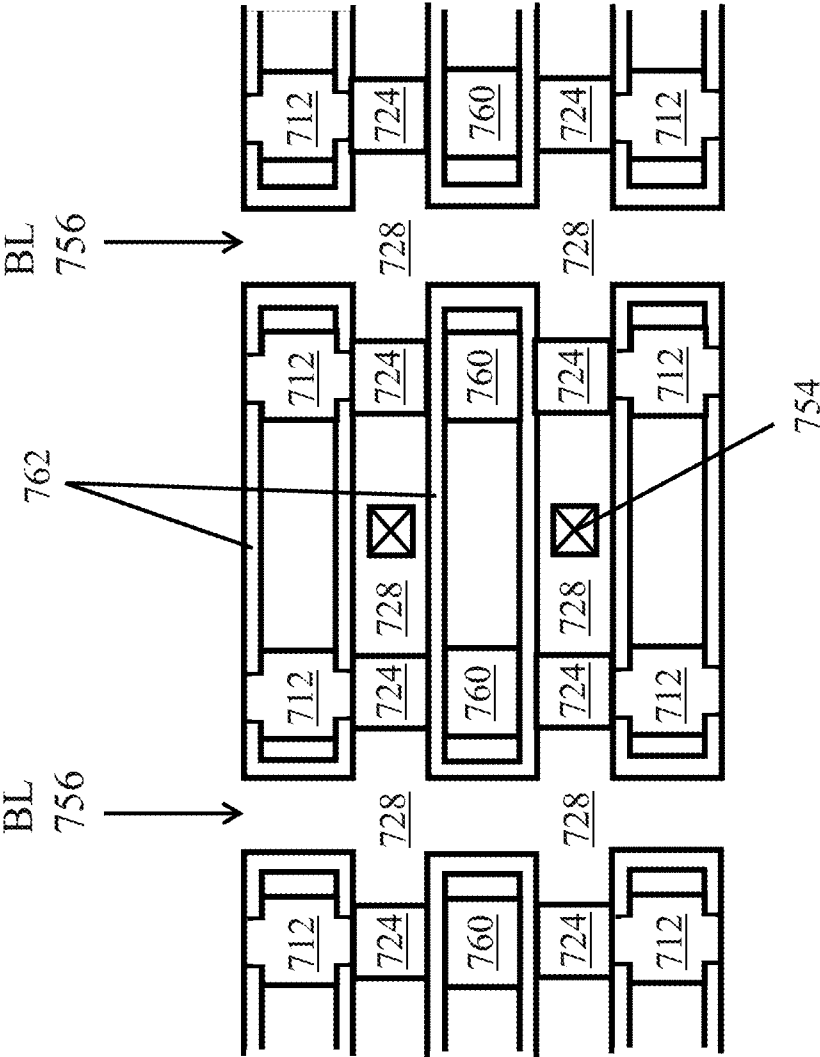


Fig. 7J

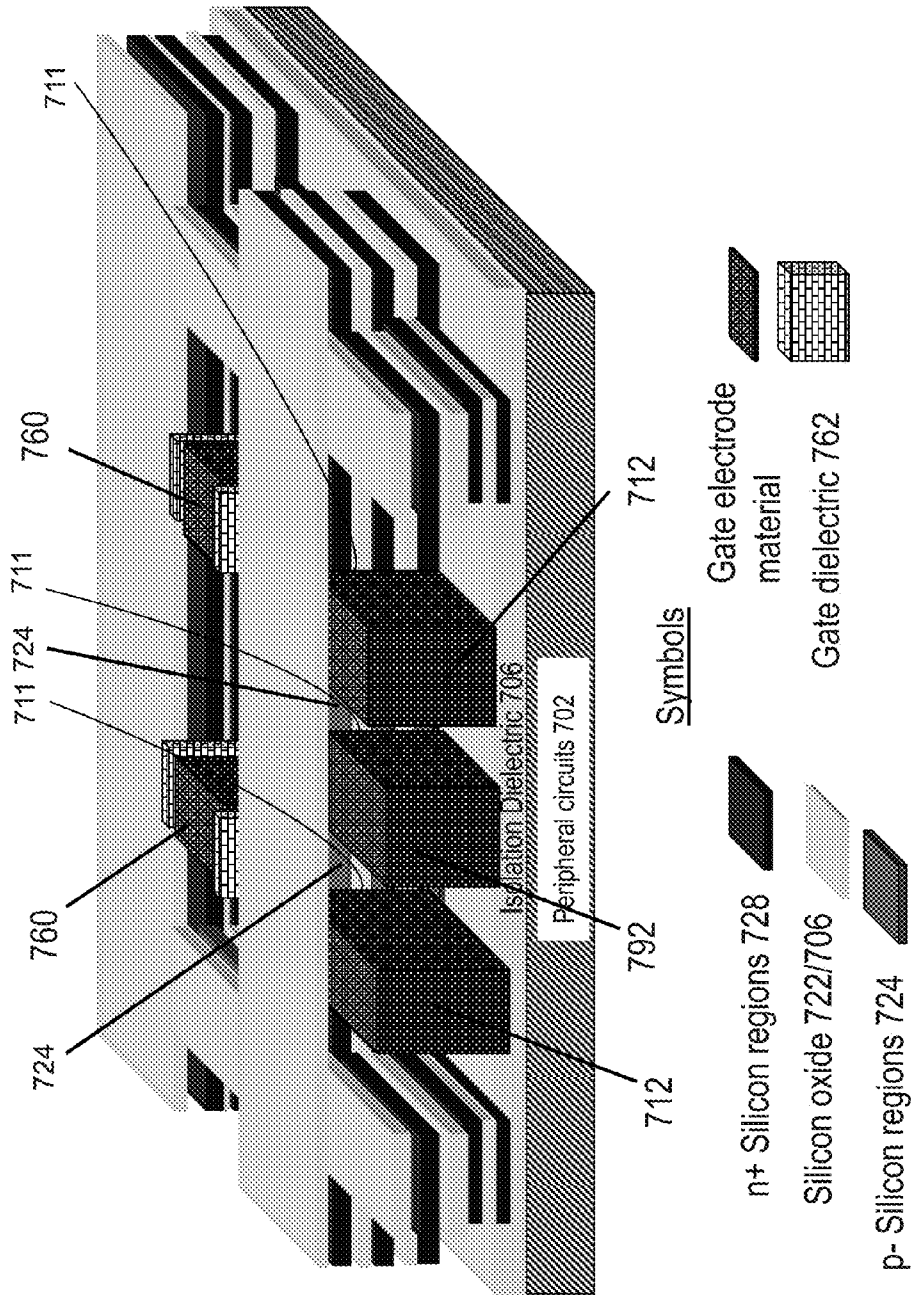


Fig. 7K

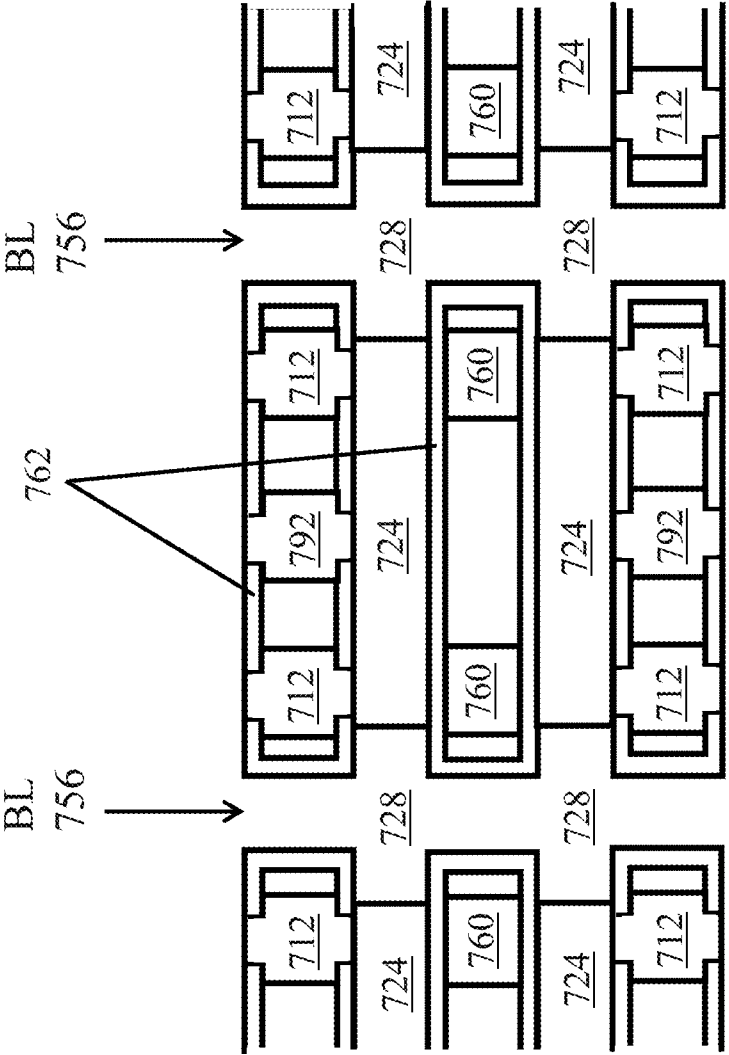


Fig. 7L

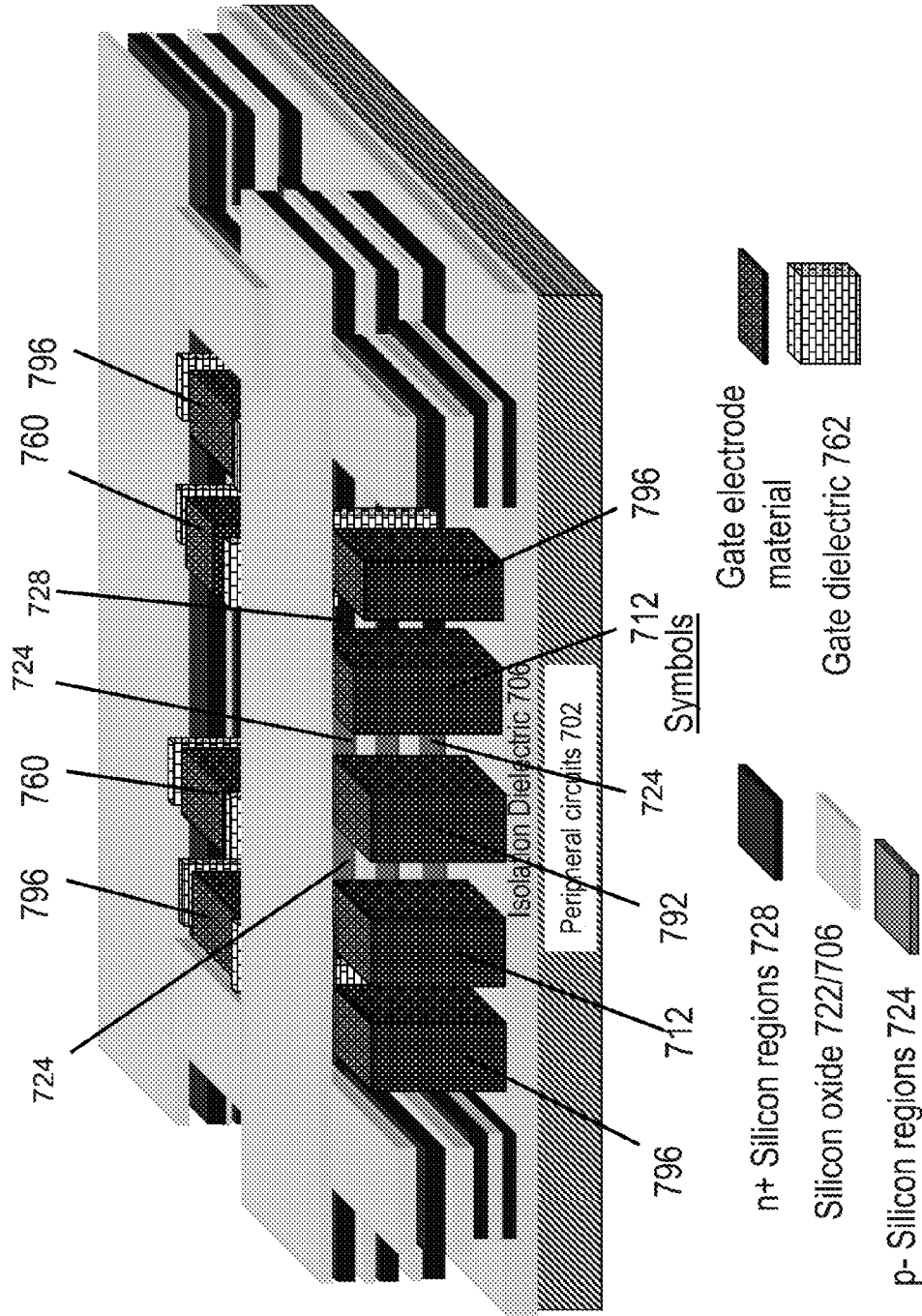


Fig. 7M

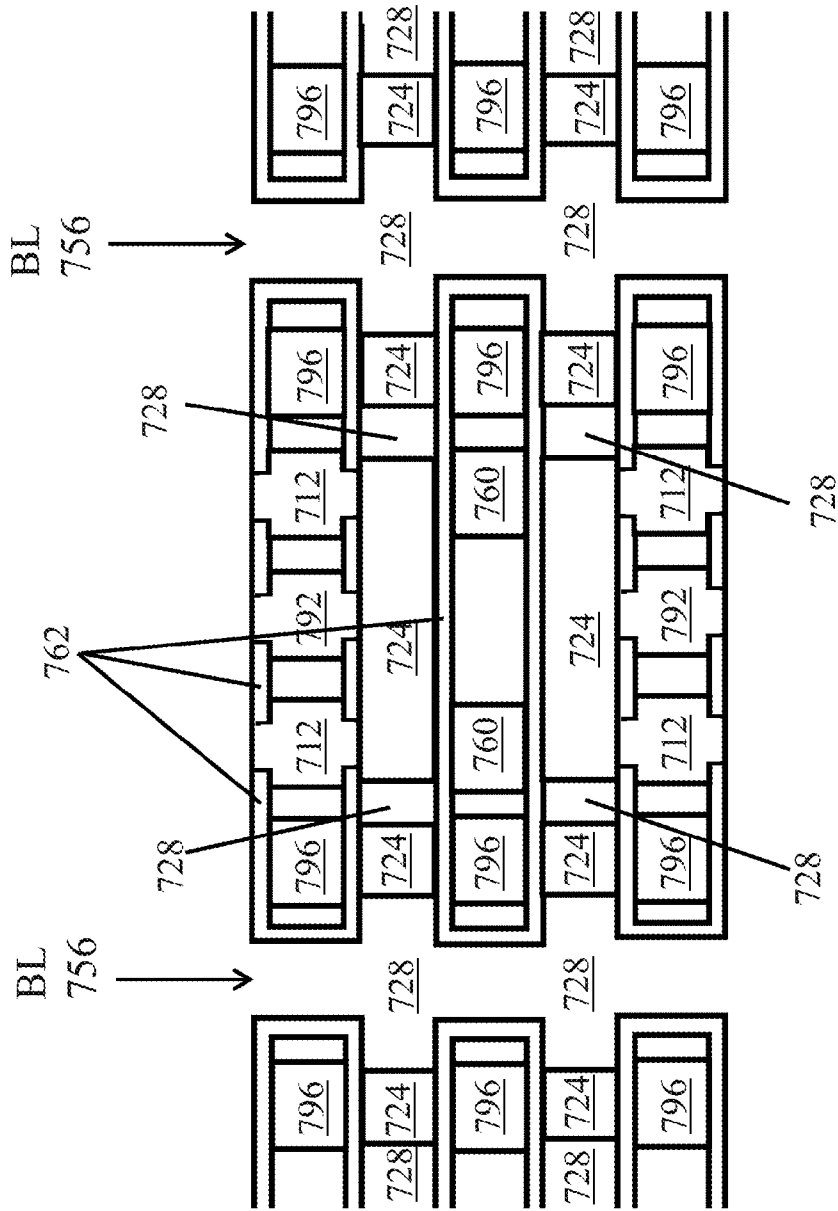


Fig. 7N

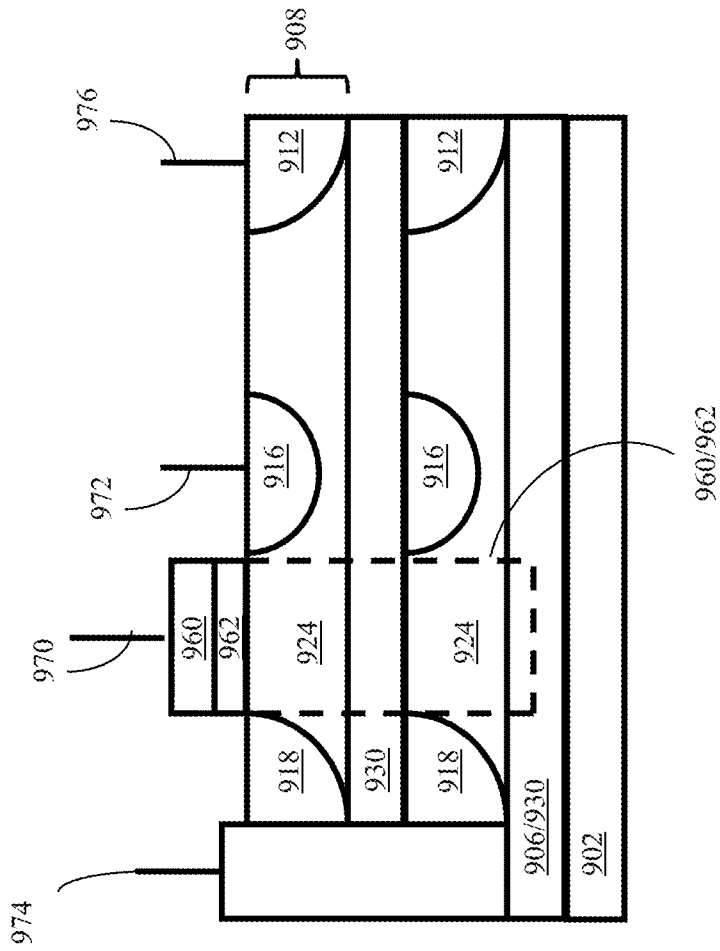


Fig. 9

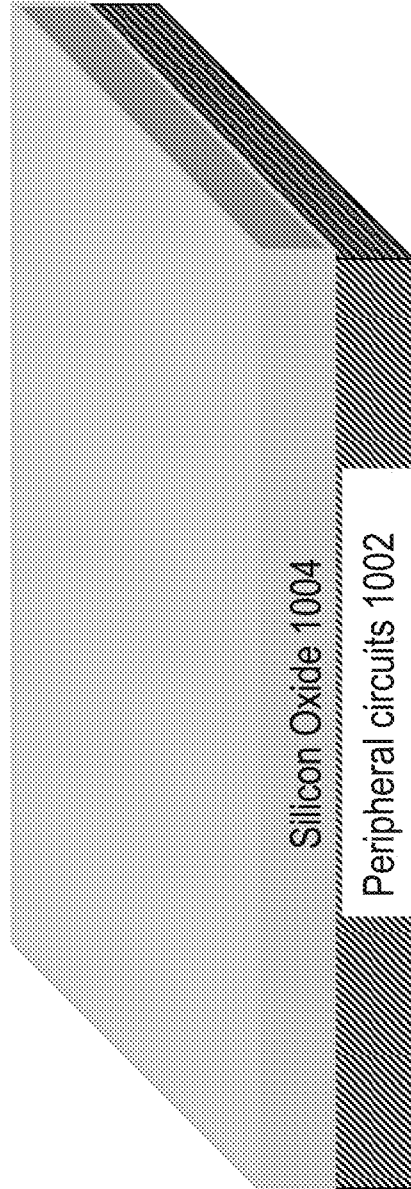


Fig. 10A

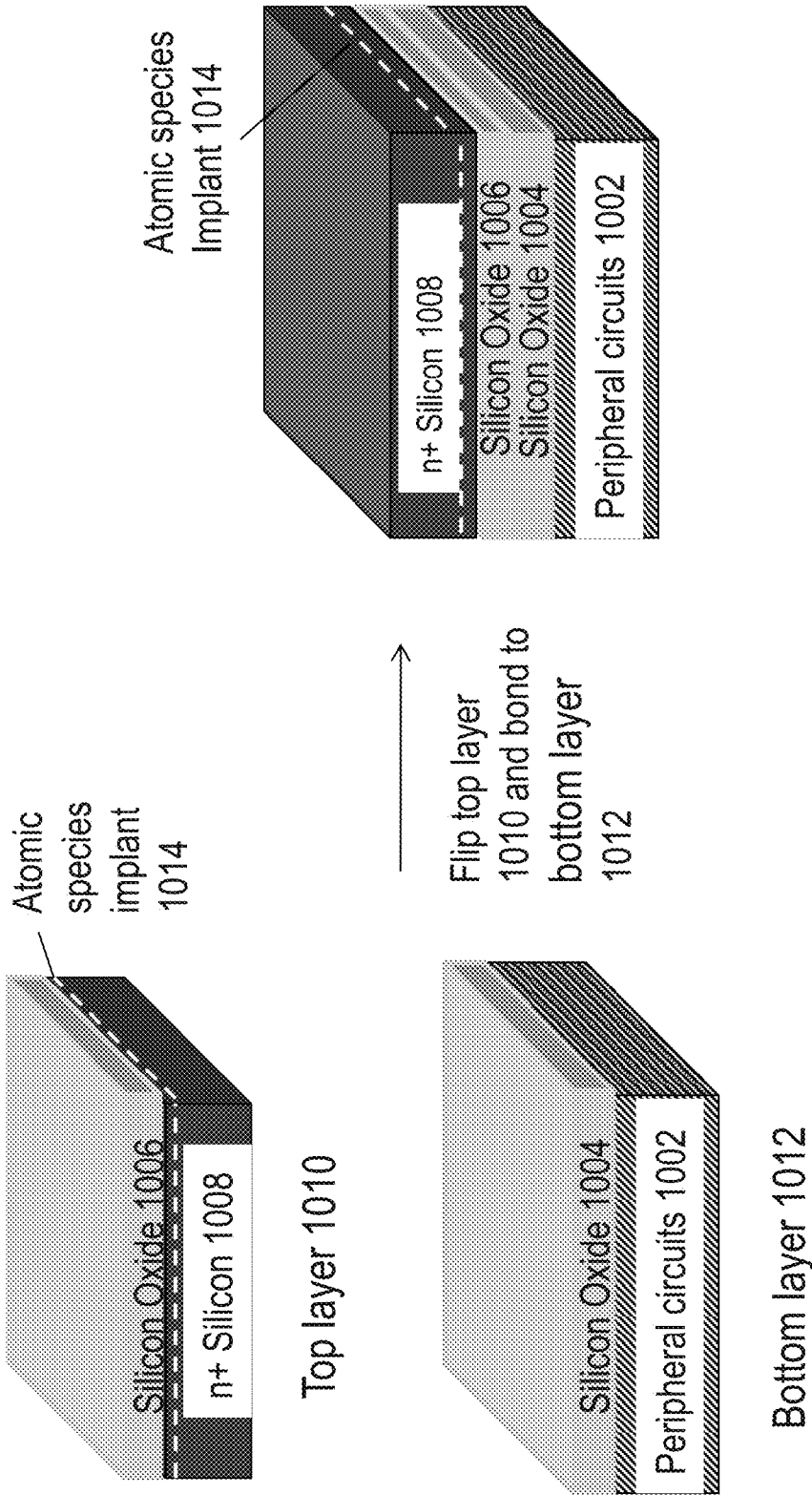


Fig. 10B

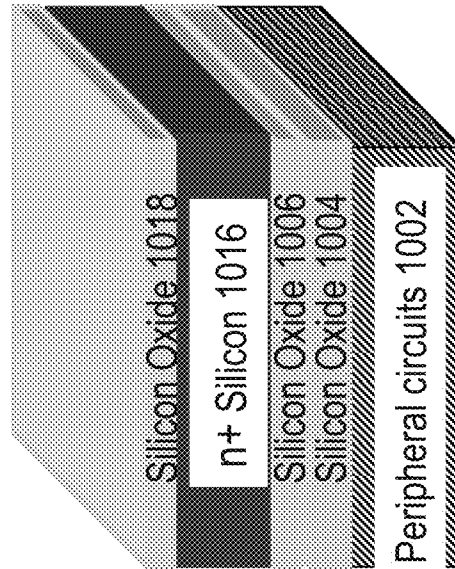


Fig. 10C

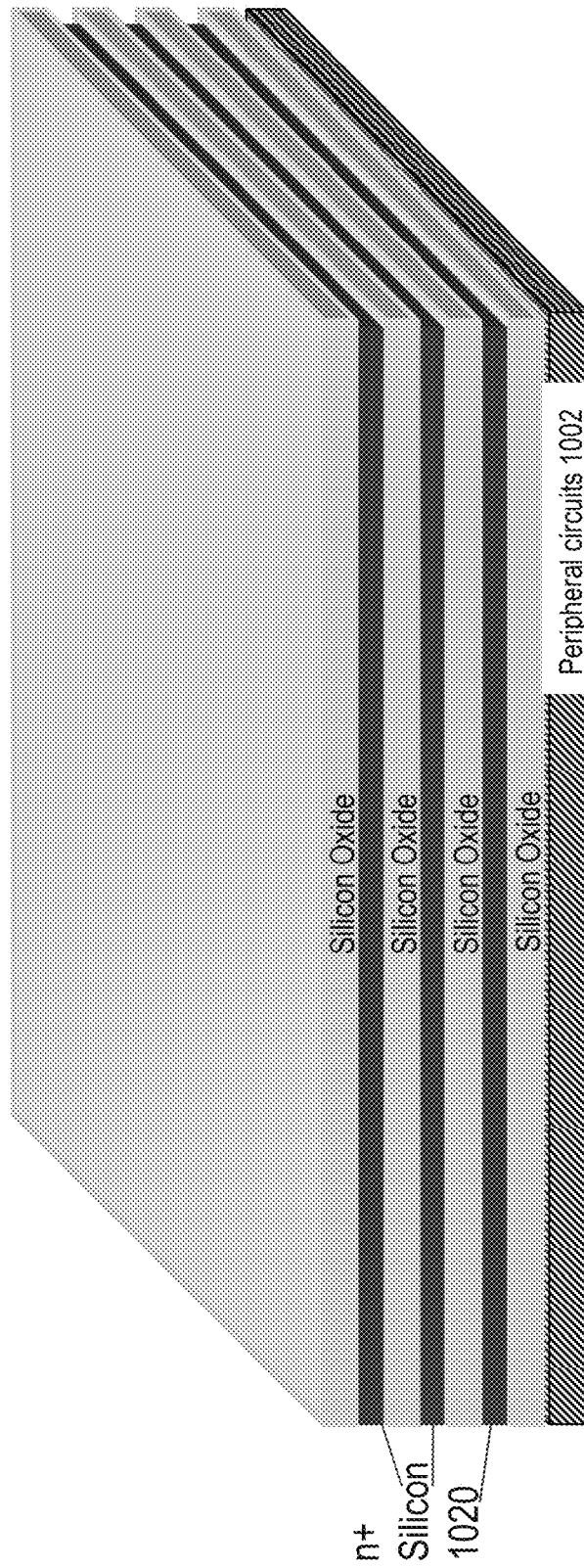


Fig. 10D

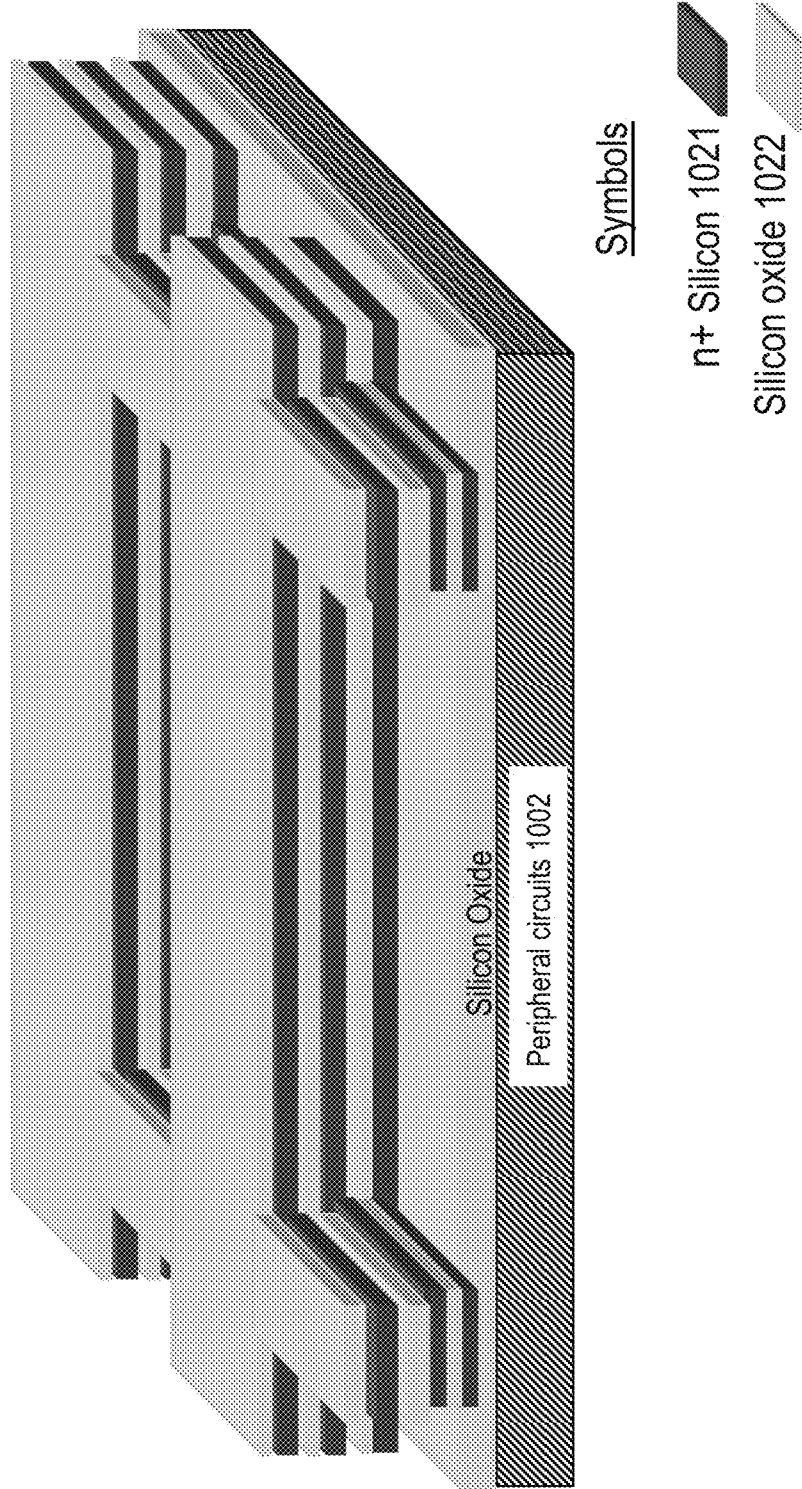


Fig. 10E

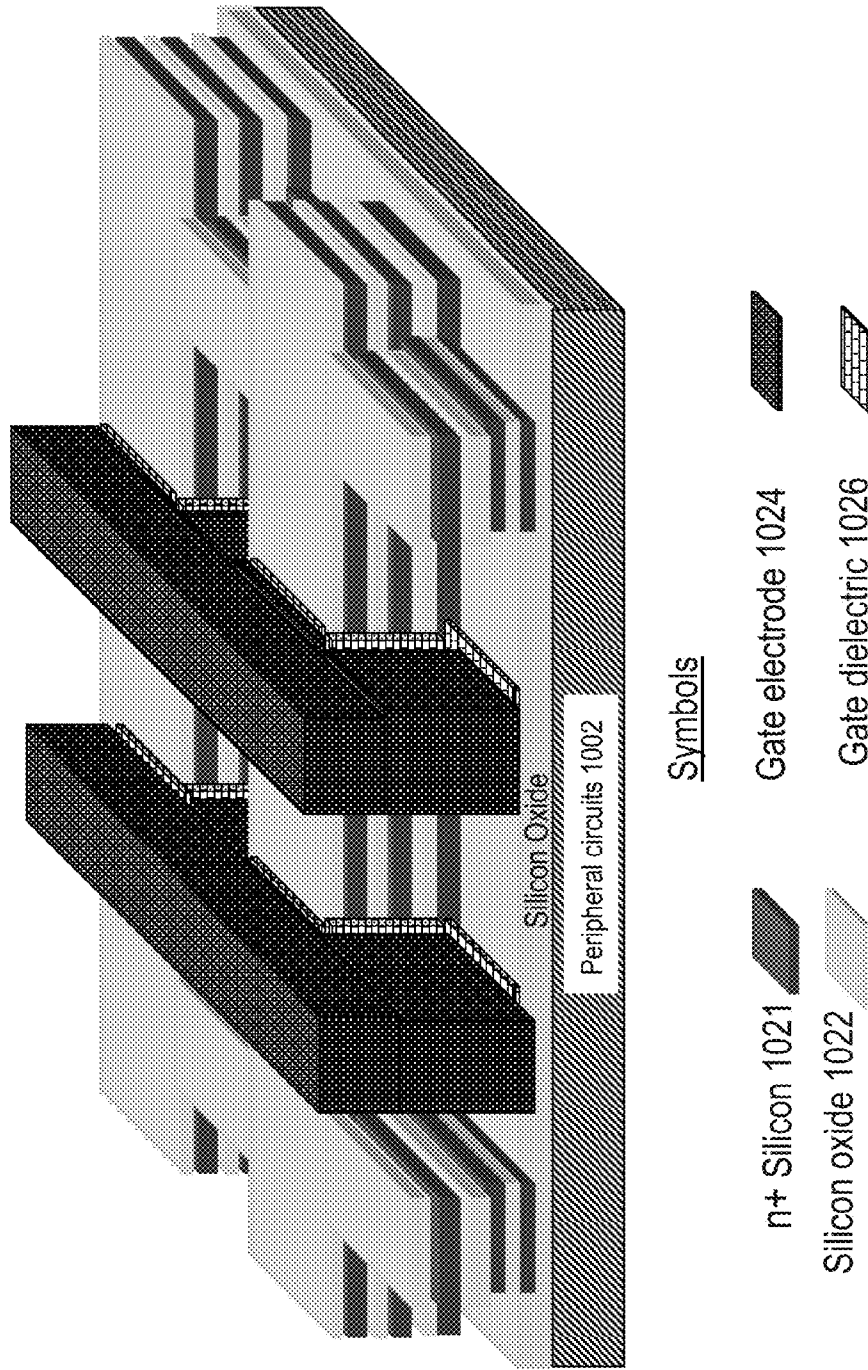


Fig. 10F

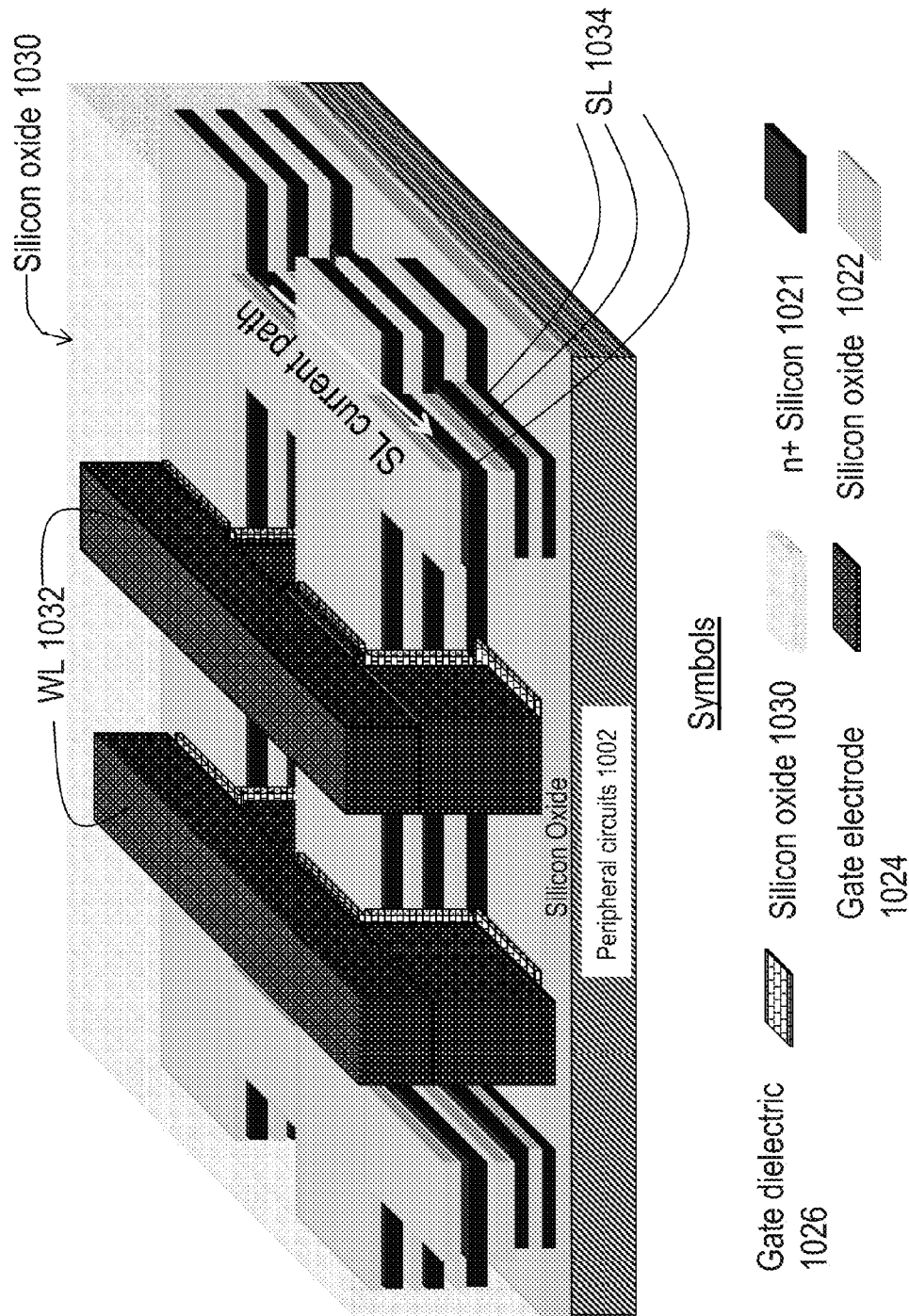


Fig. 10G

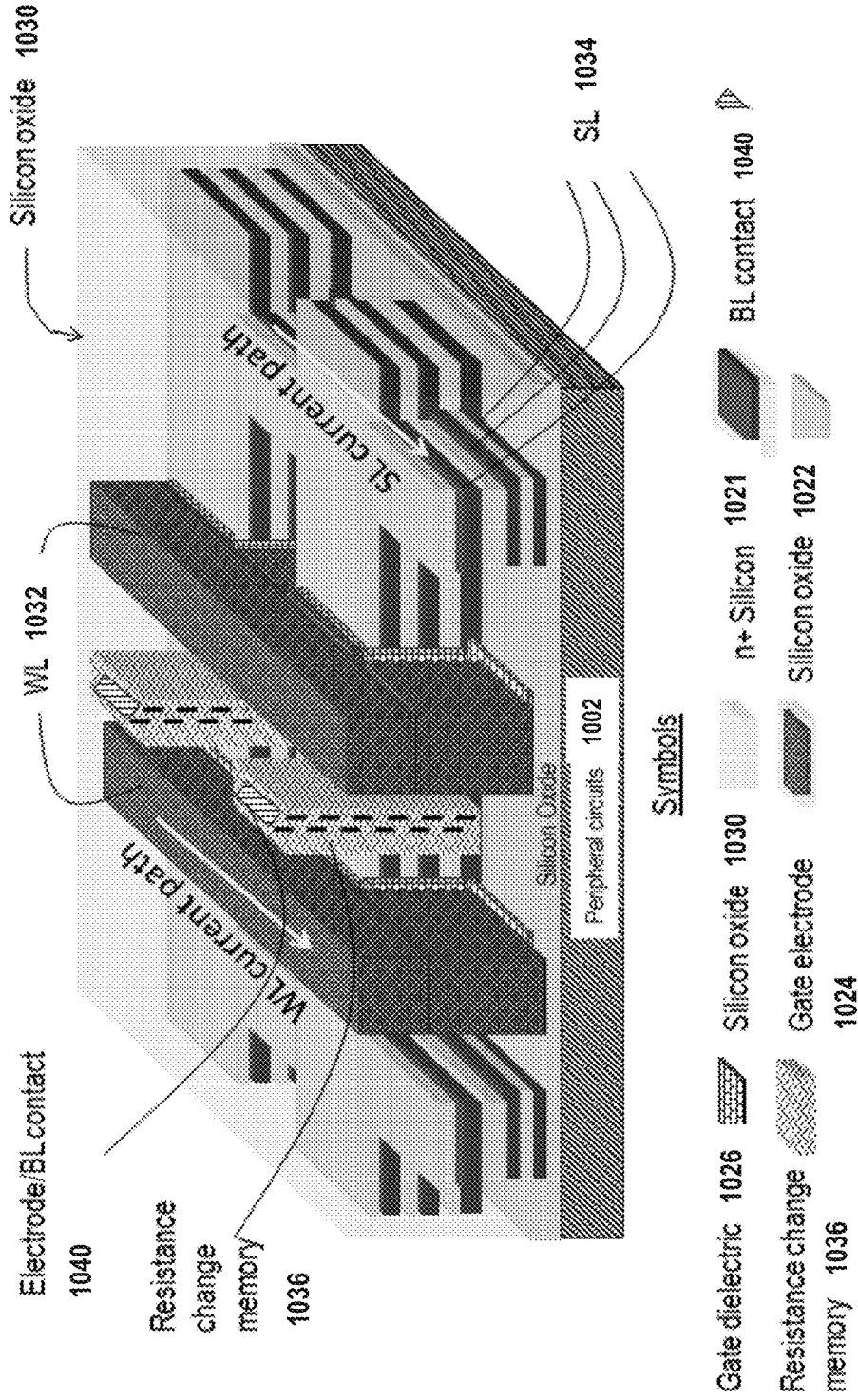


Fig. 10H

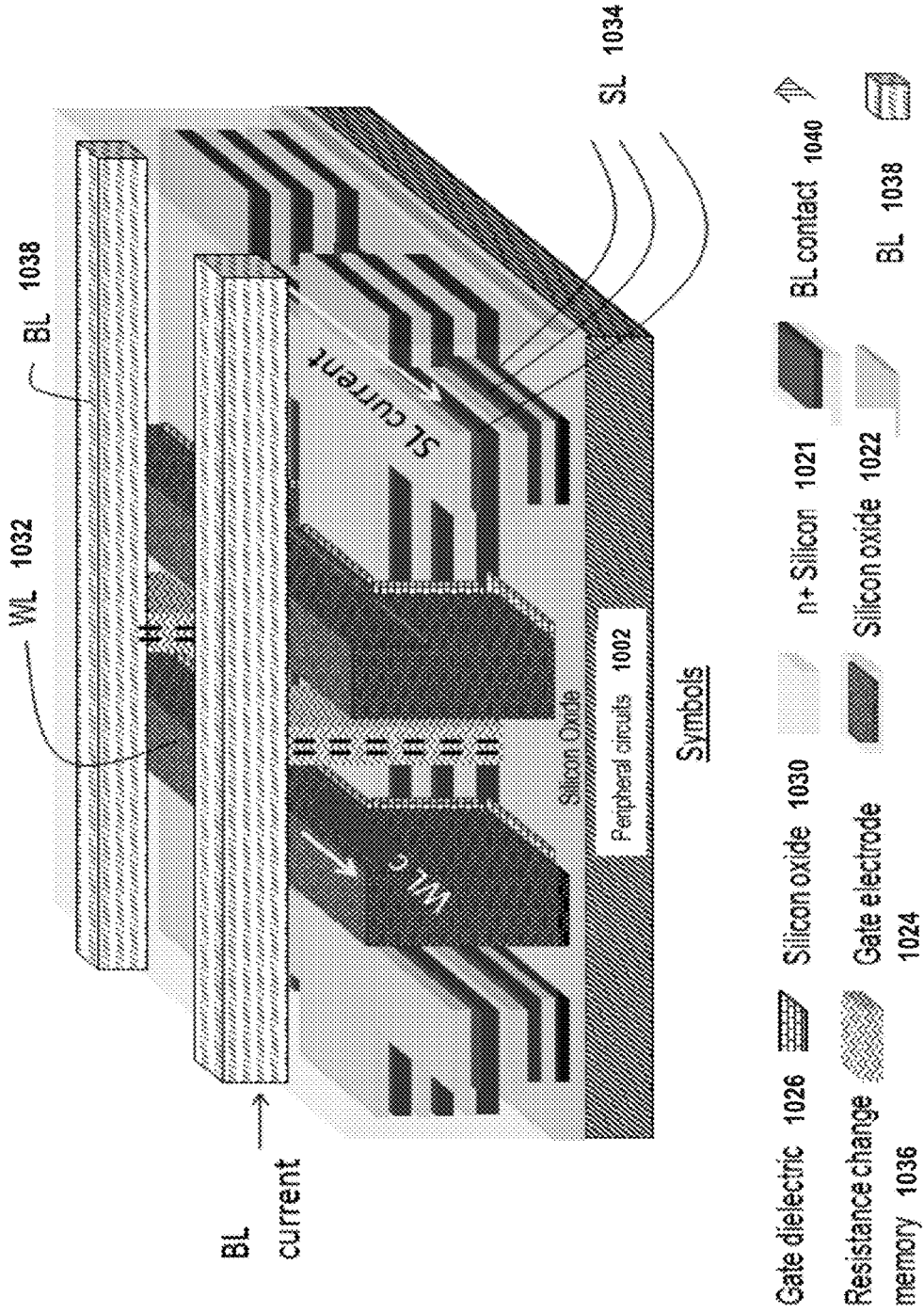


Fig. 10I

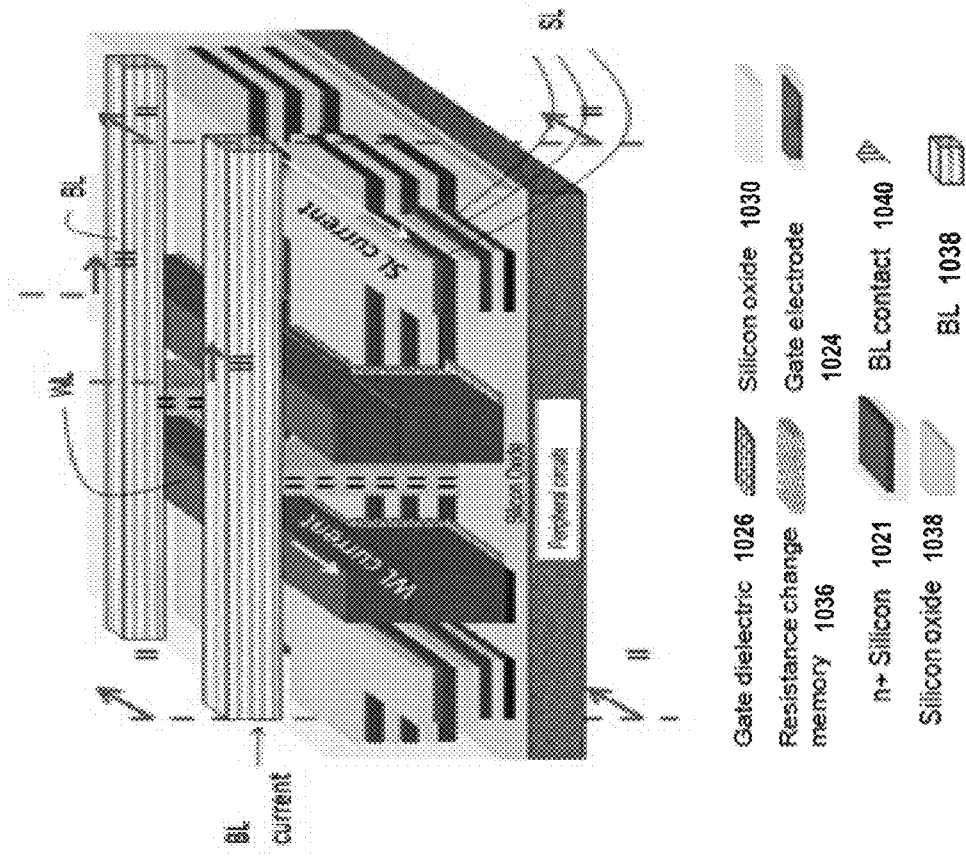
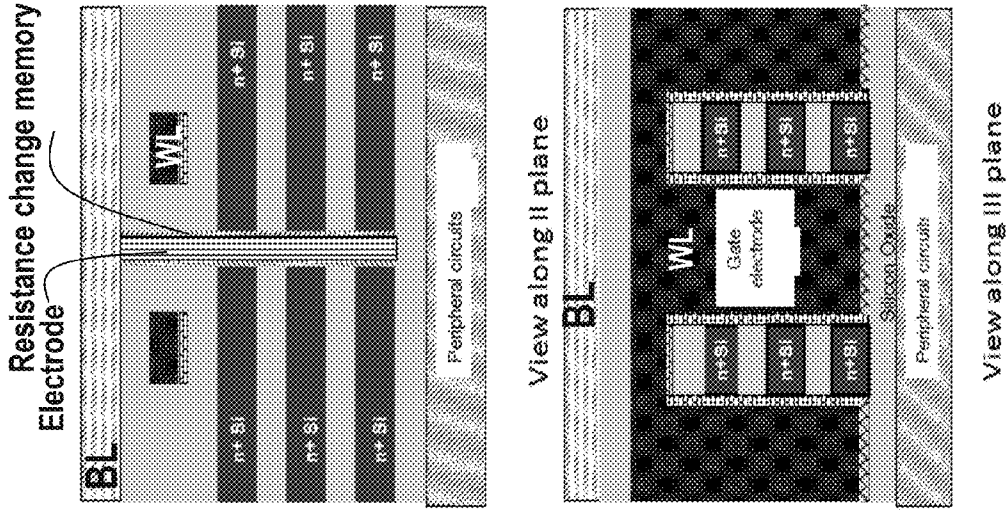


Fig. 10J

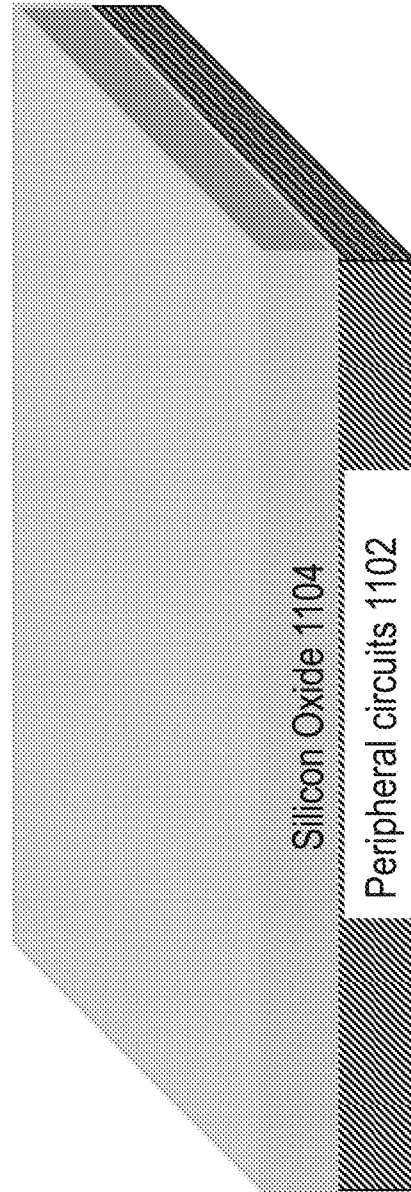


Fig. 11A

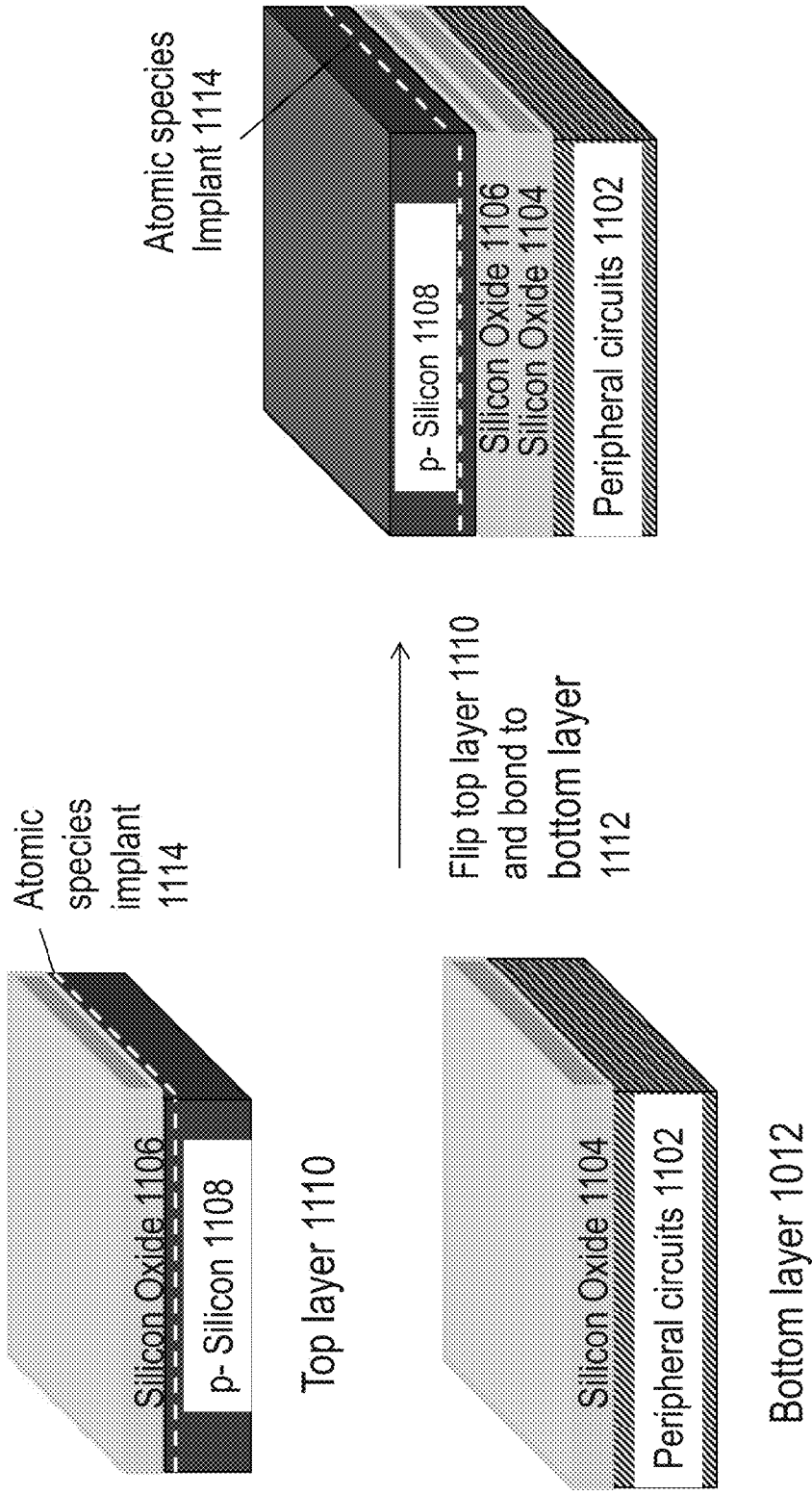


Fig. 11B

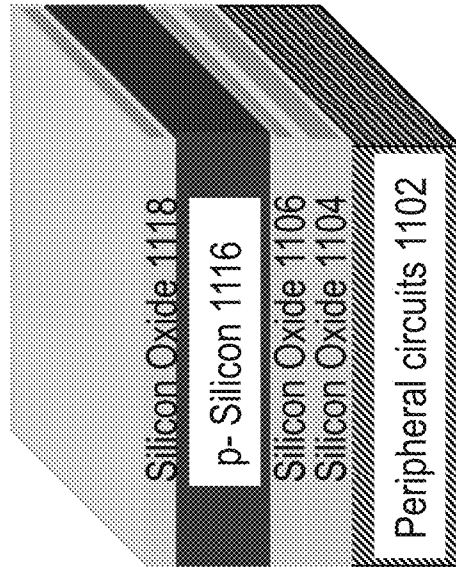


Fig. 11C

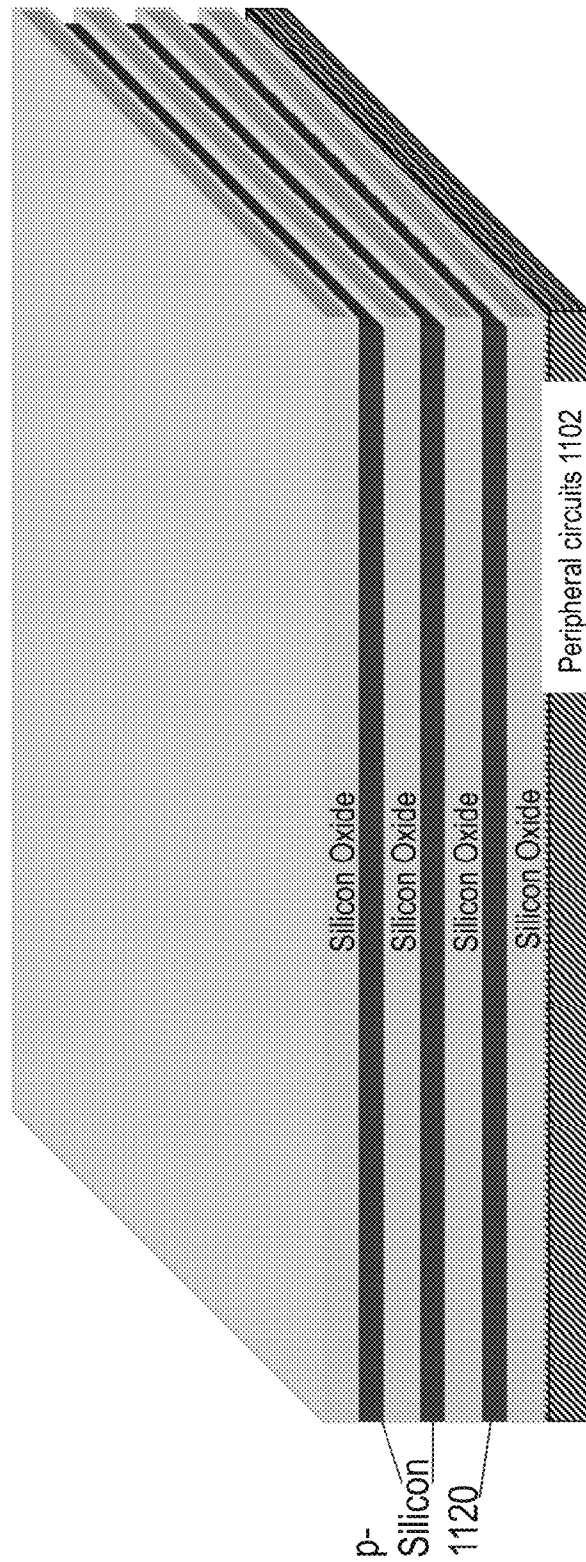


Fig. 11D

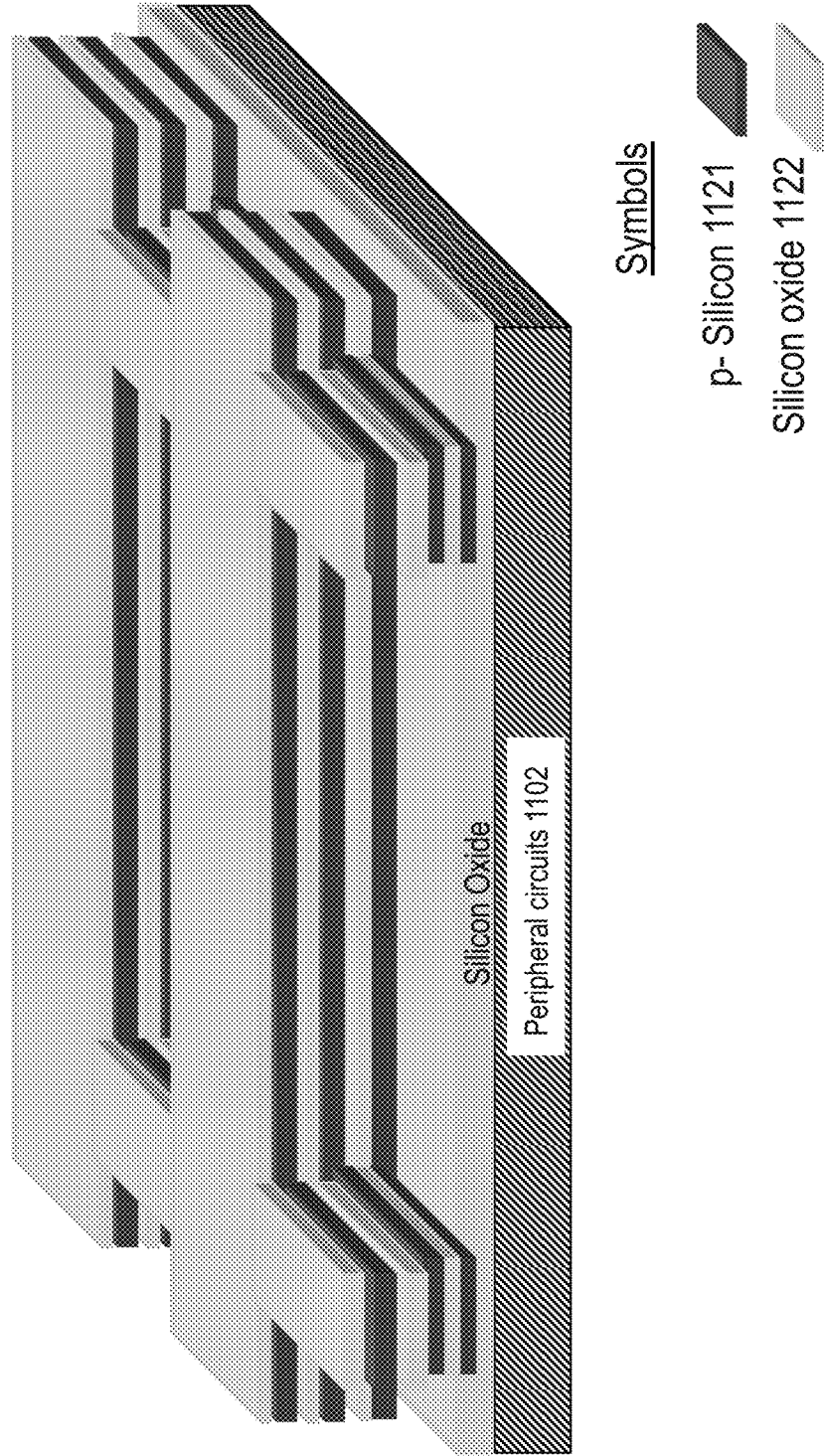


Fig. 11E

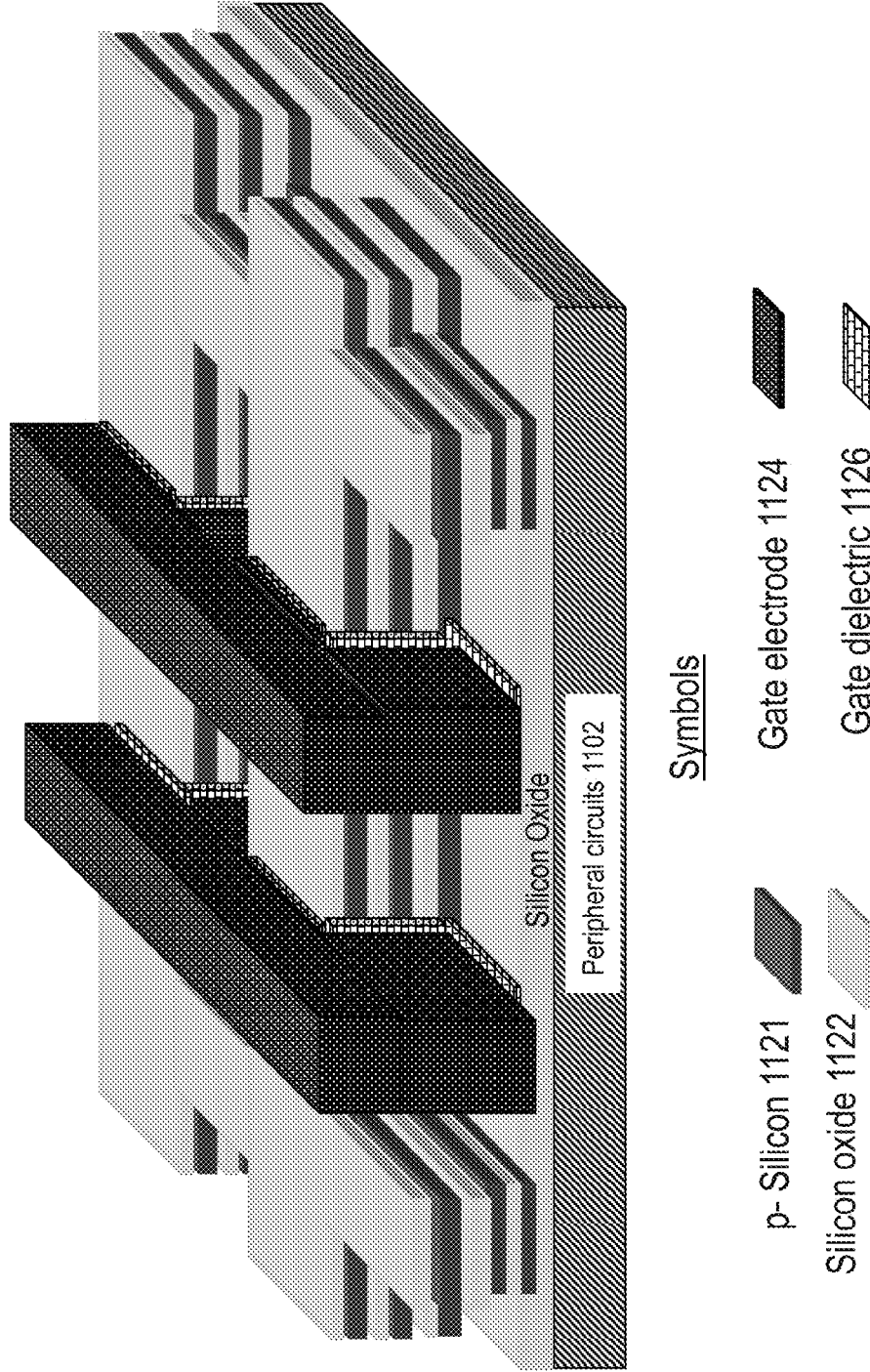


Fig. 11F

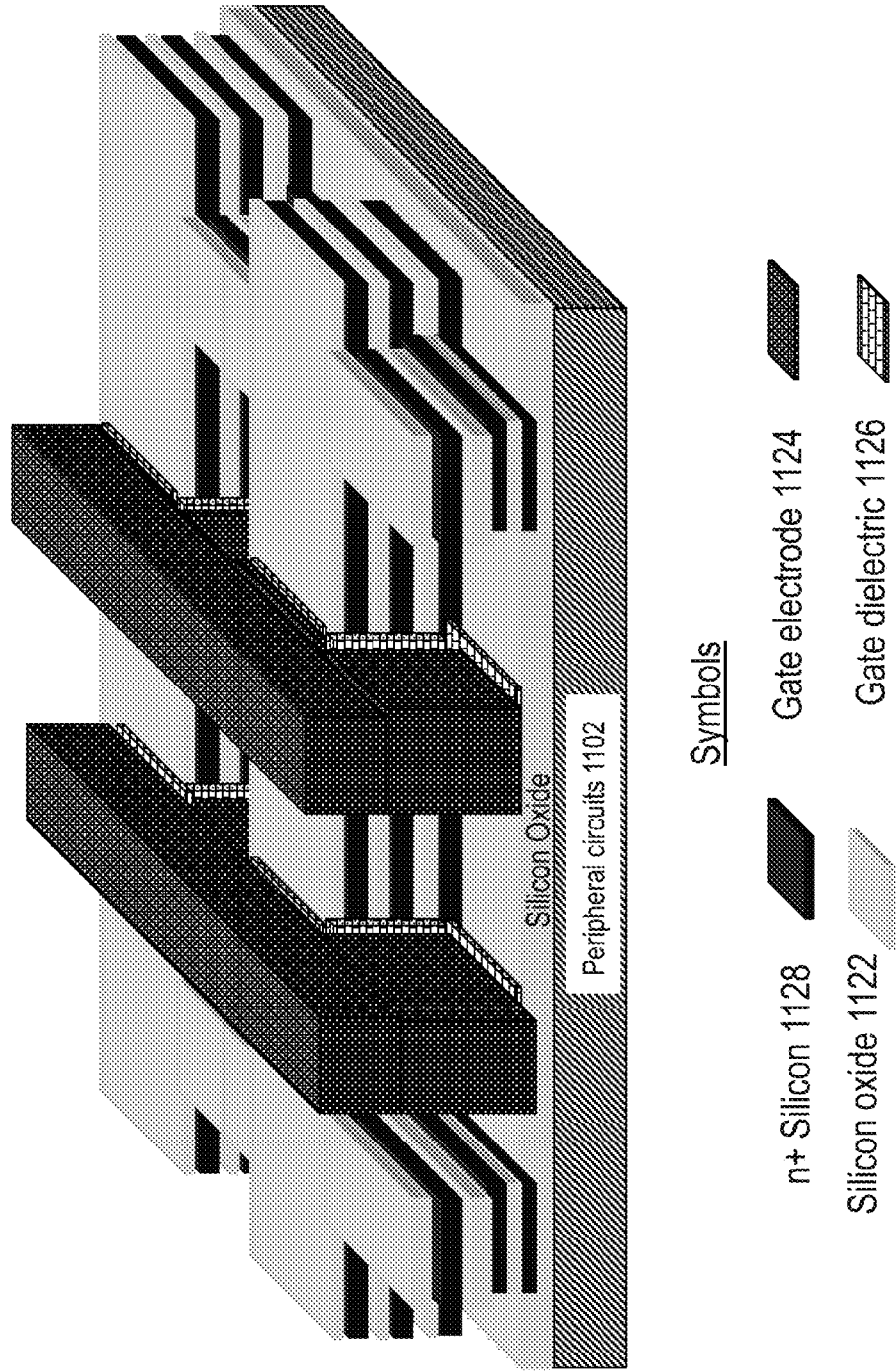


Fig. 11G

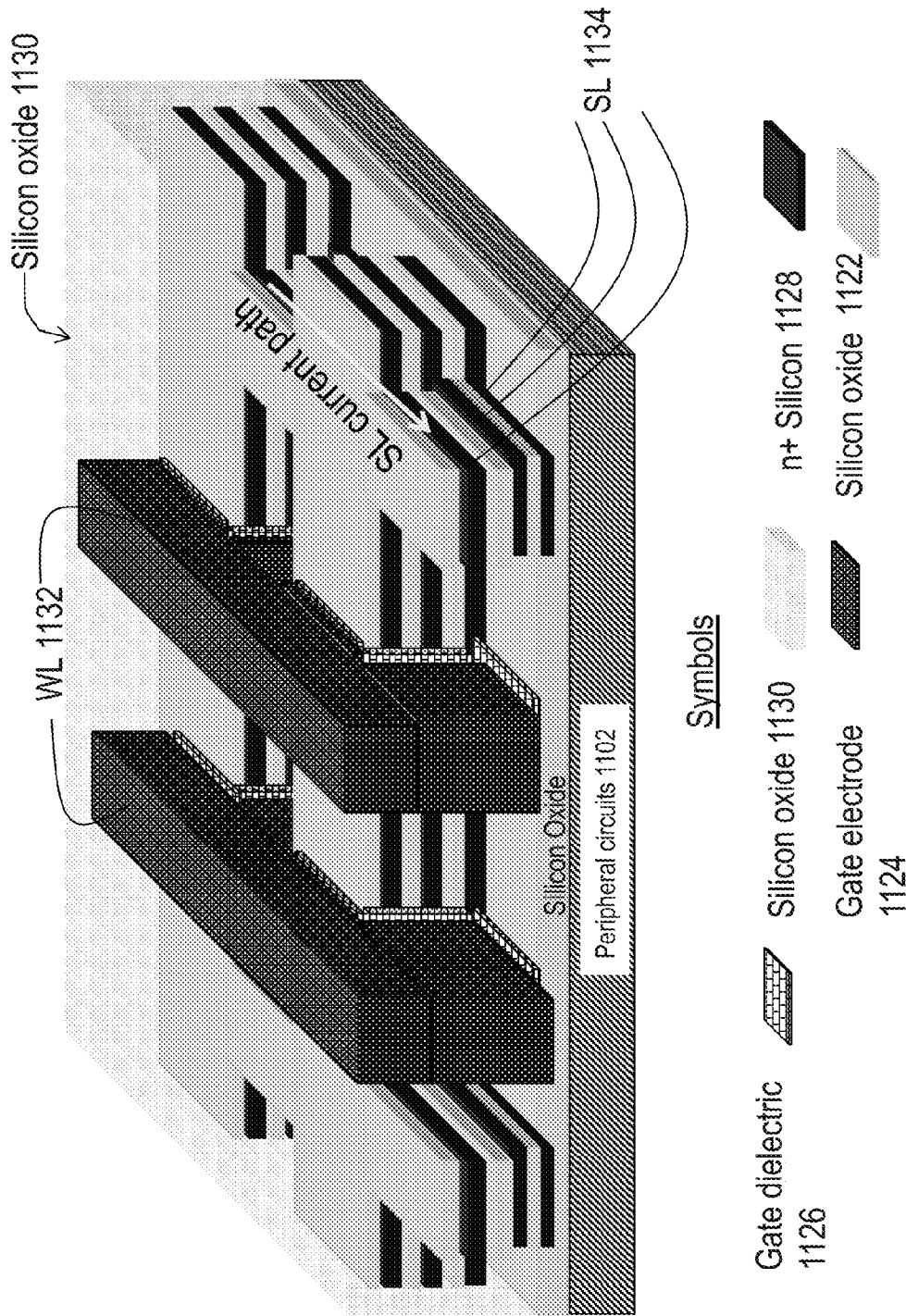


Fig. 11H

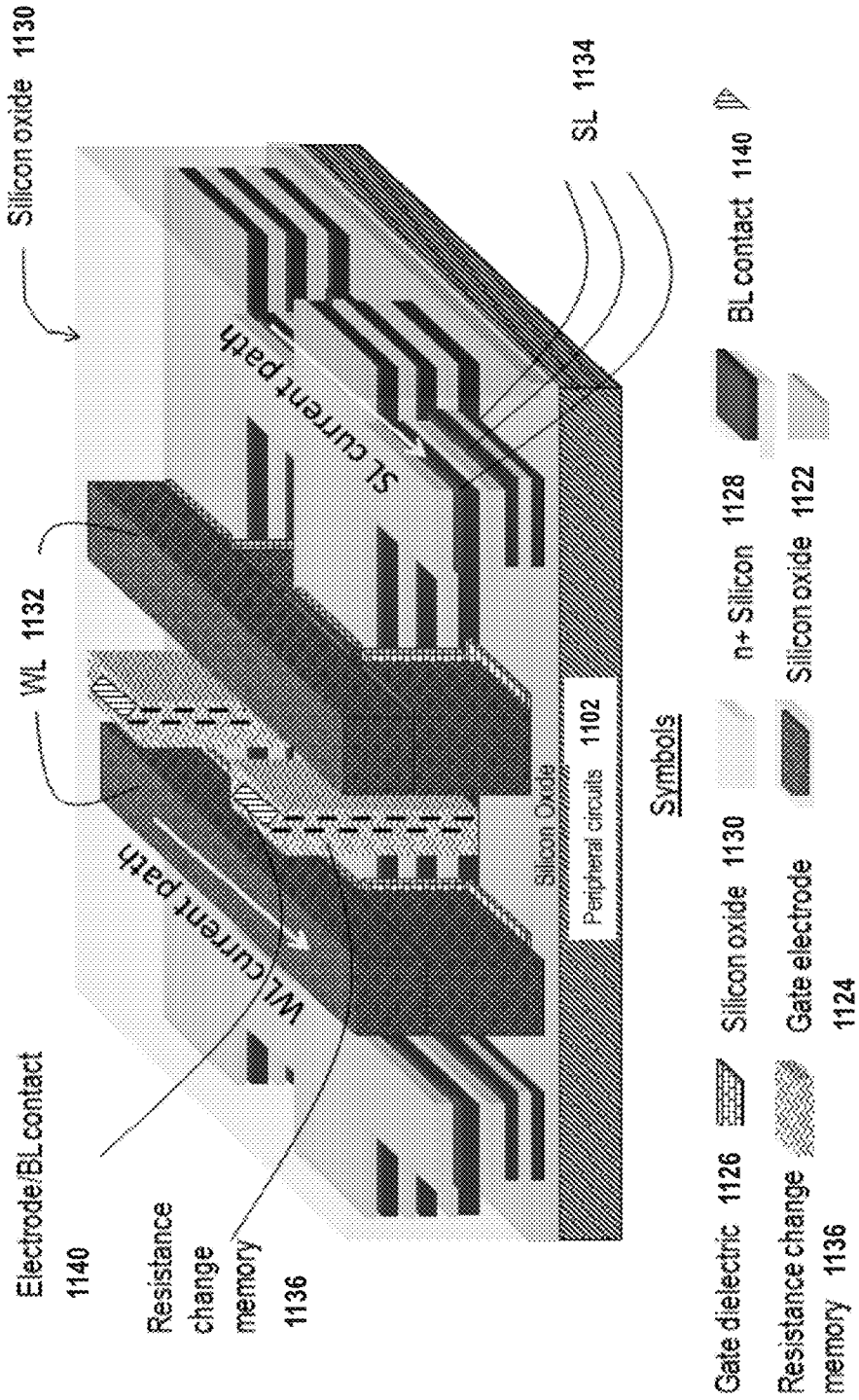


Fig. 111

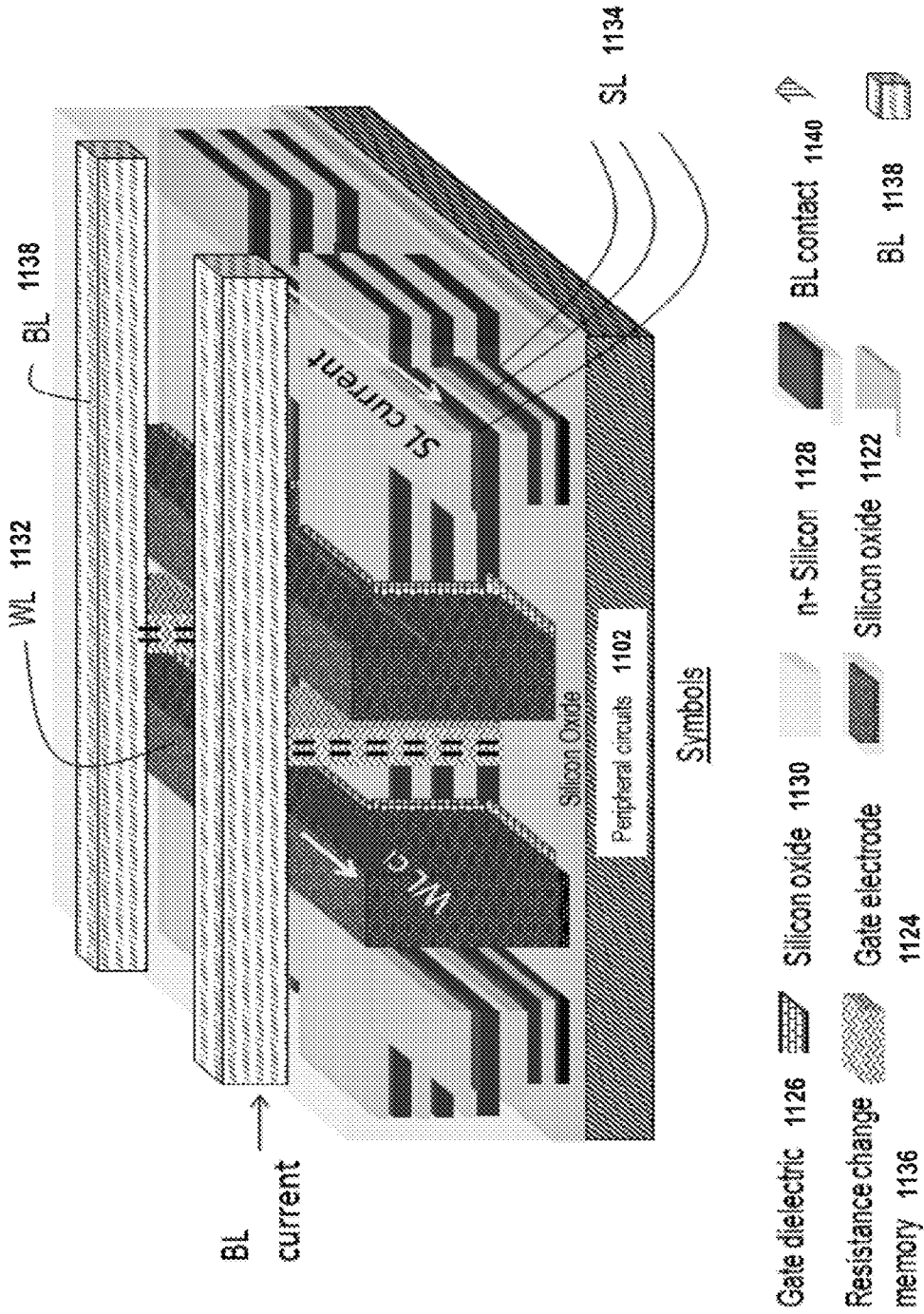


Fig. 11J

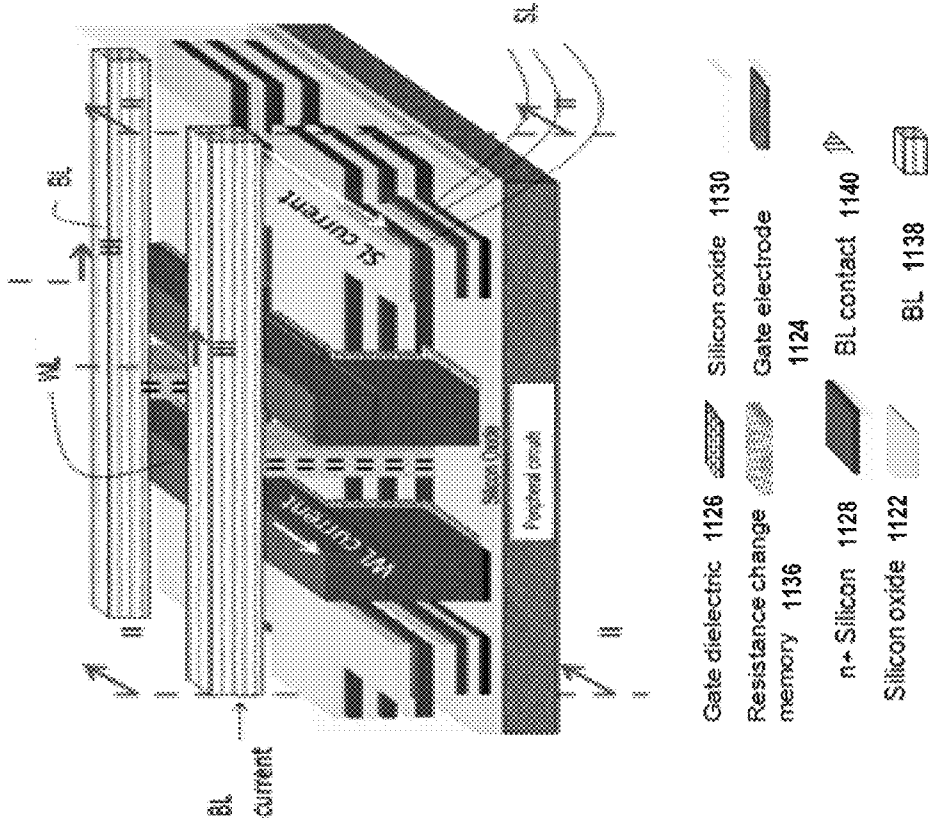
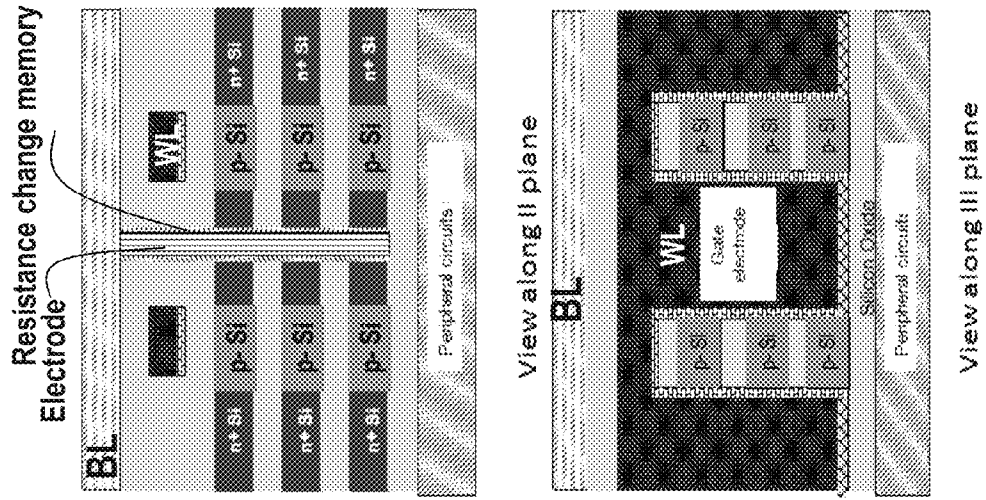


Fig. 11K

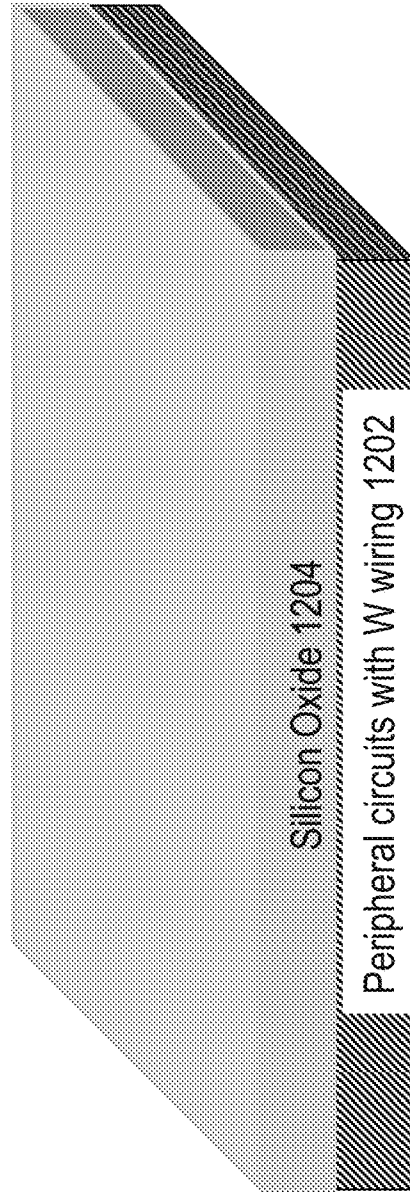


Fig. 12A

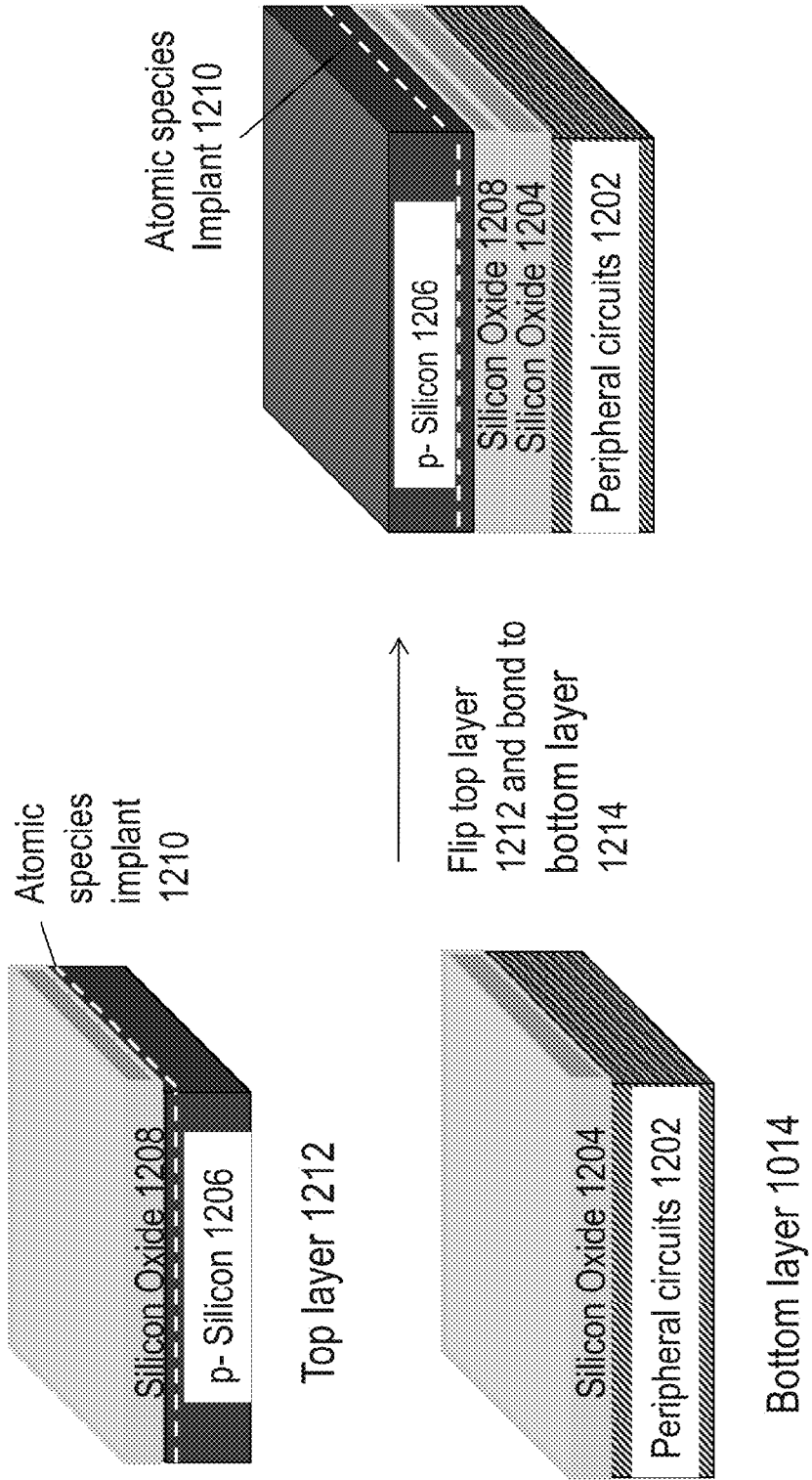


Fig. 12B

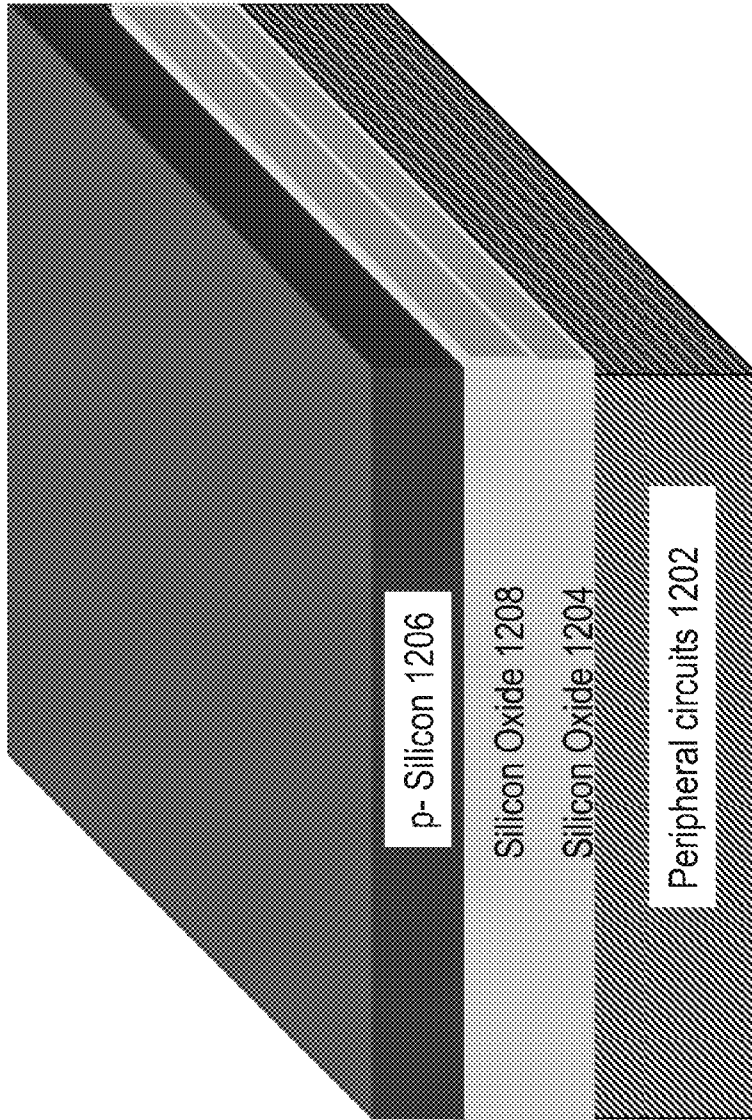


Fig. 12C

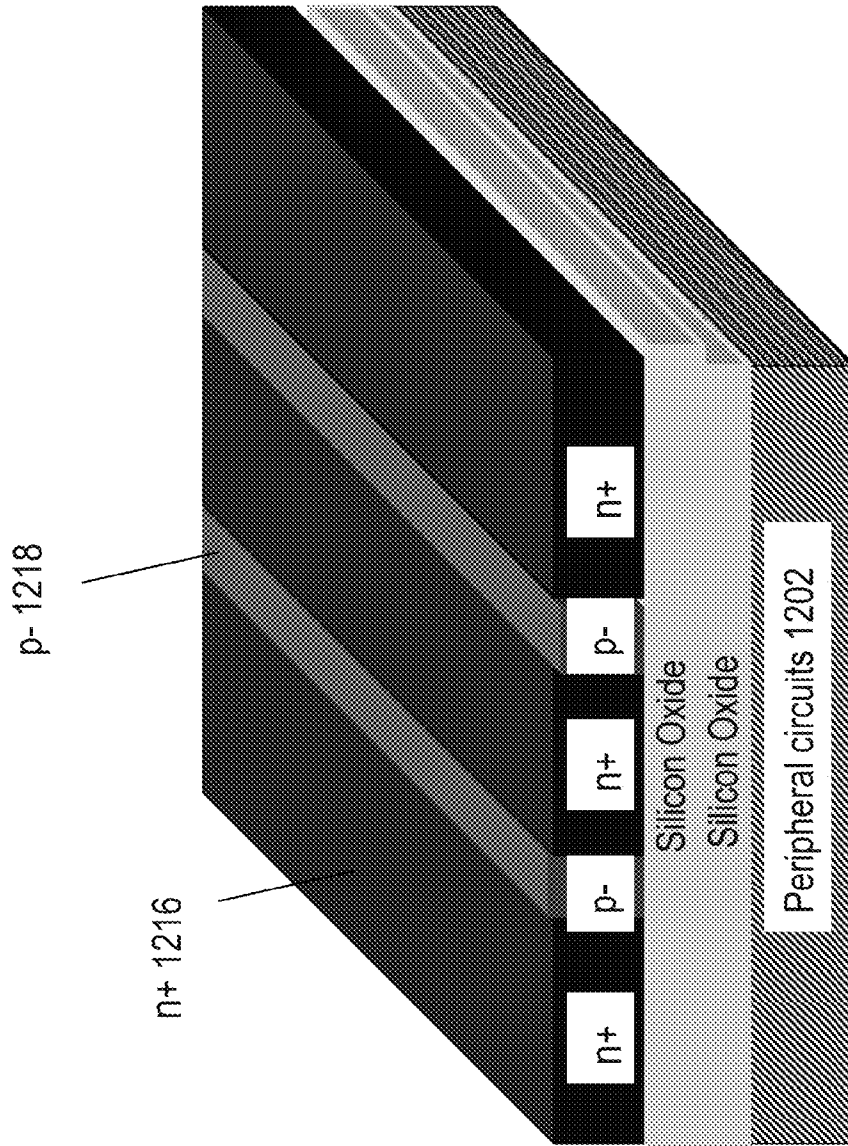


Fig. 12D

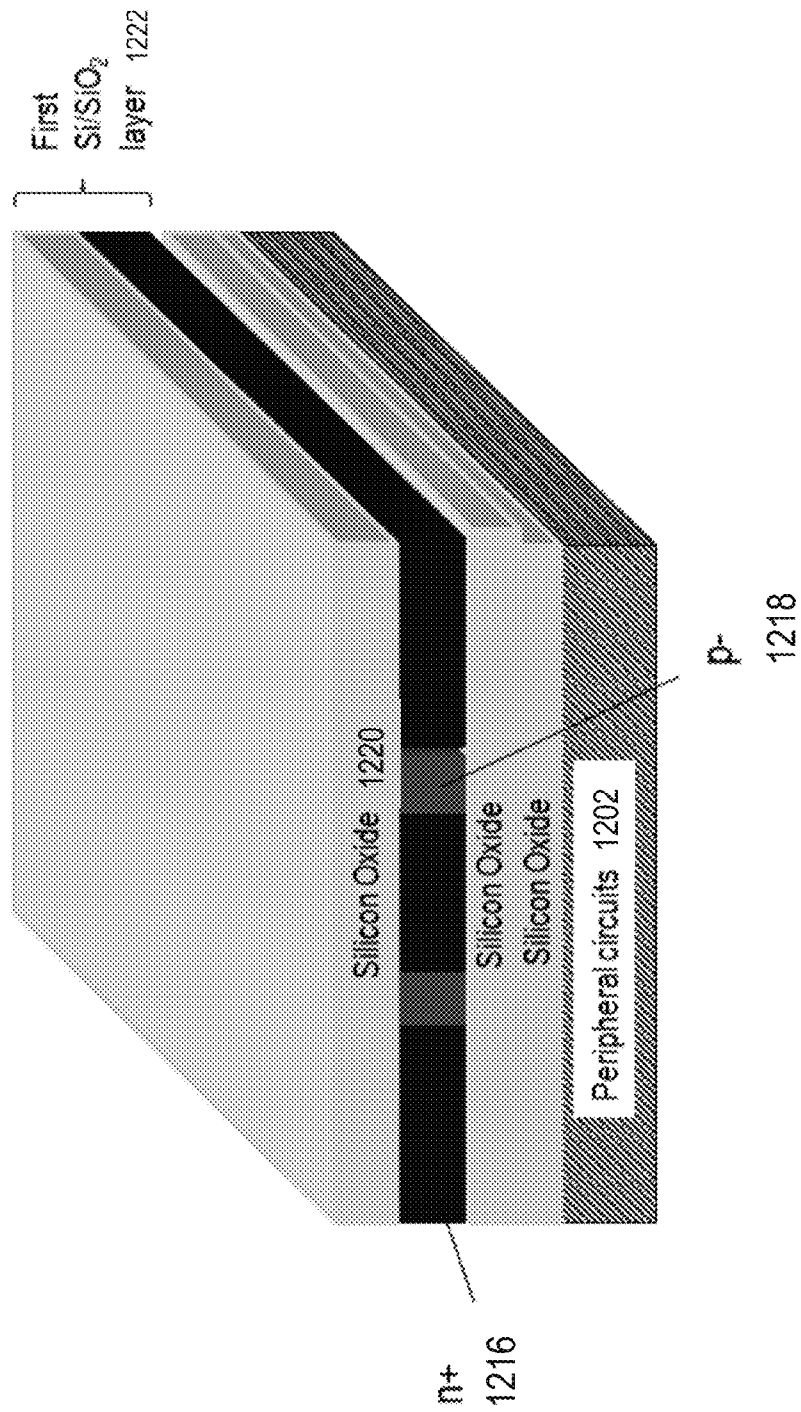


Fig. 12E

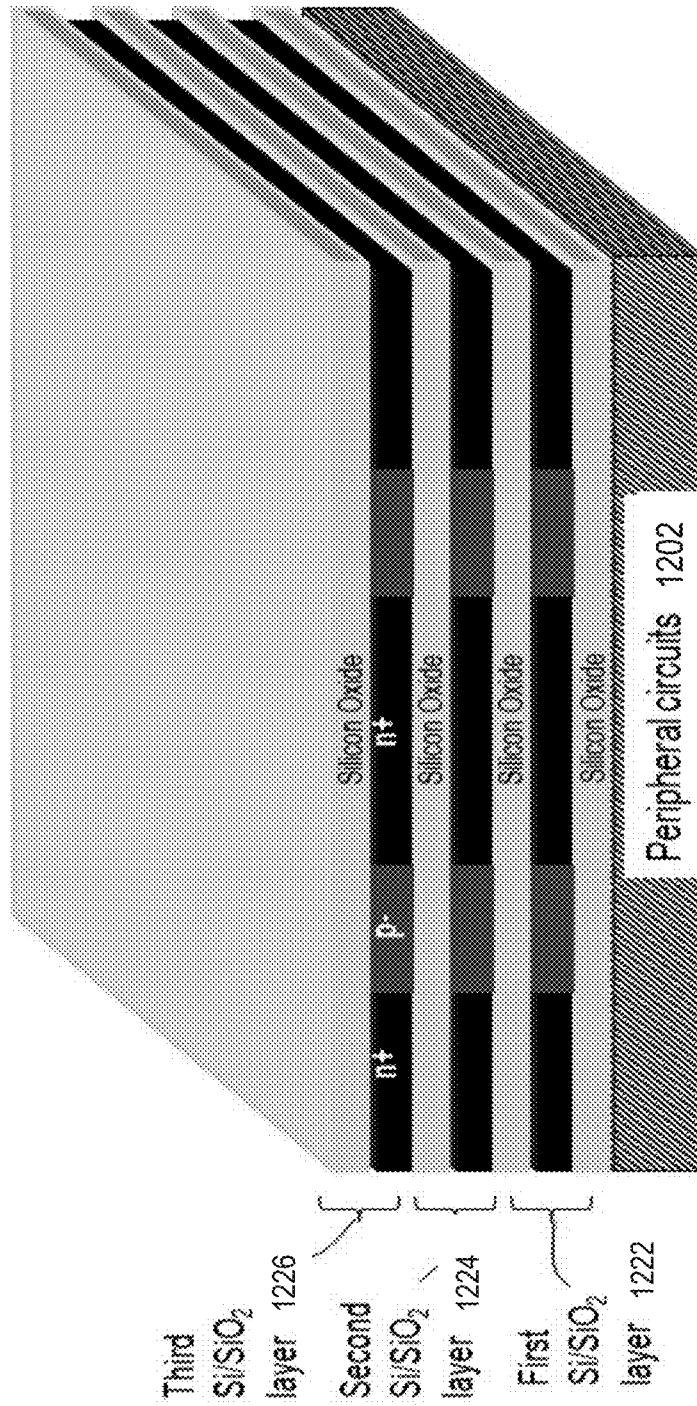


Fig. 12F

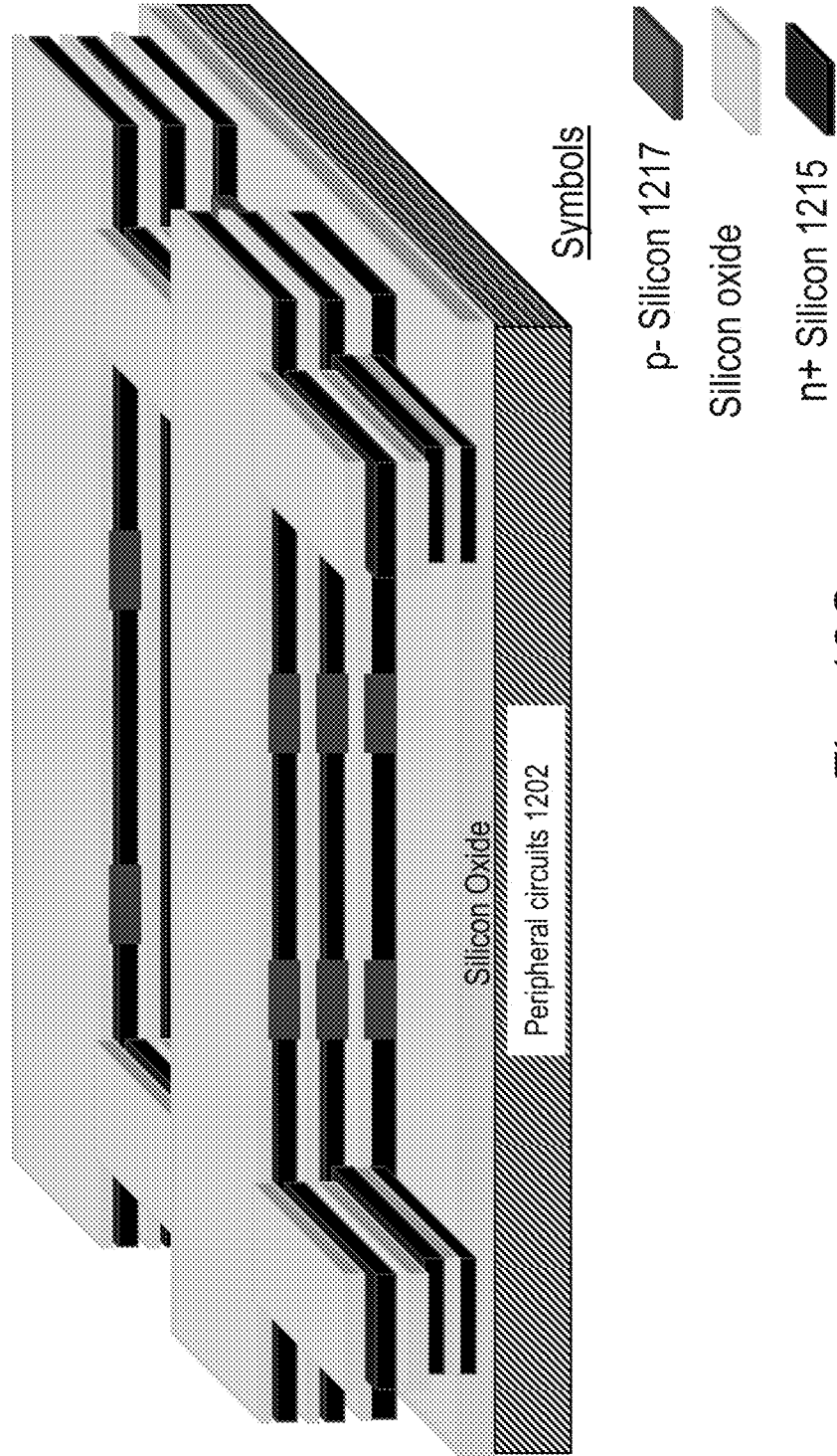


Fig. 12G

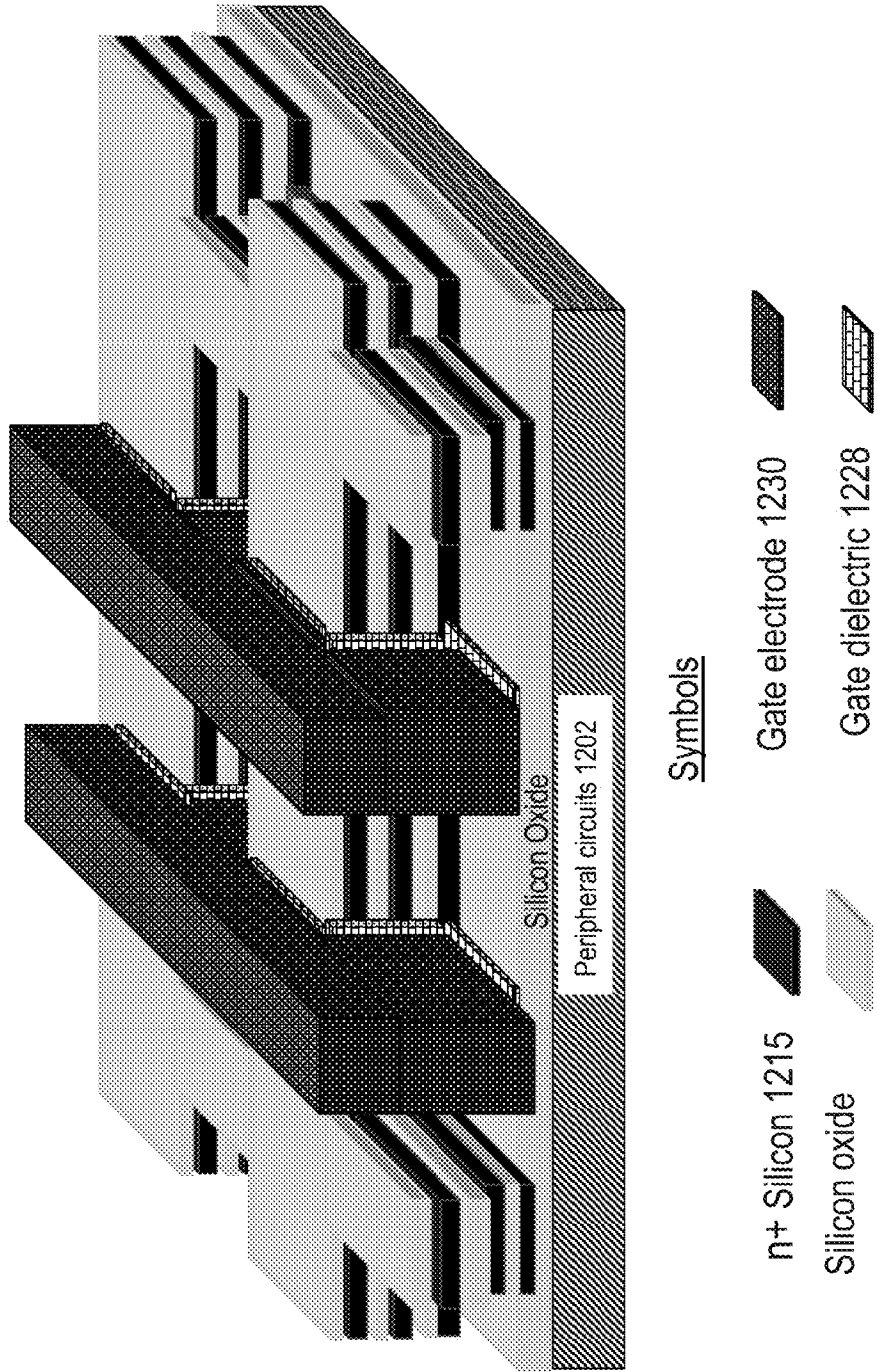


Fig. 12H

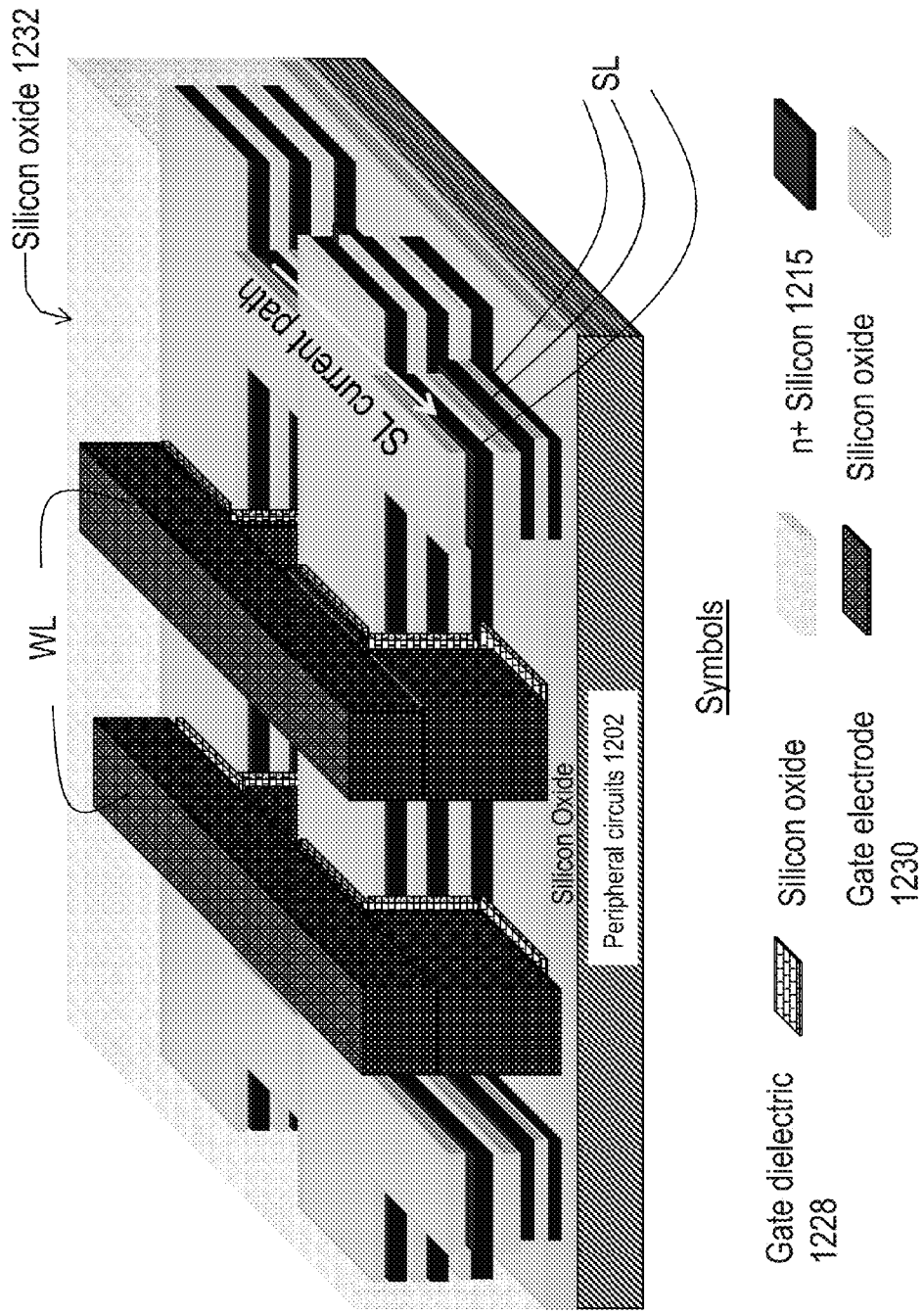


Fig. 12I

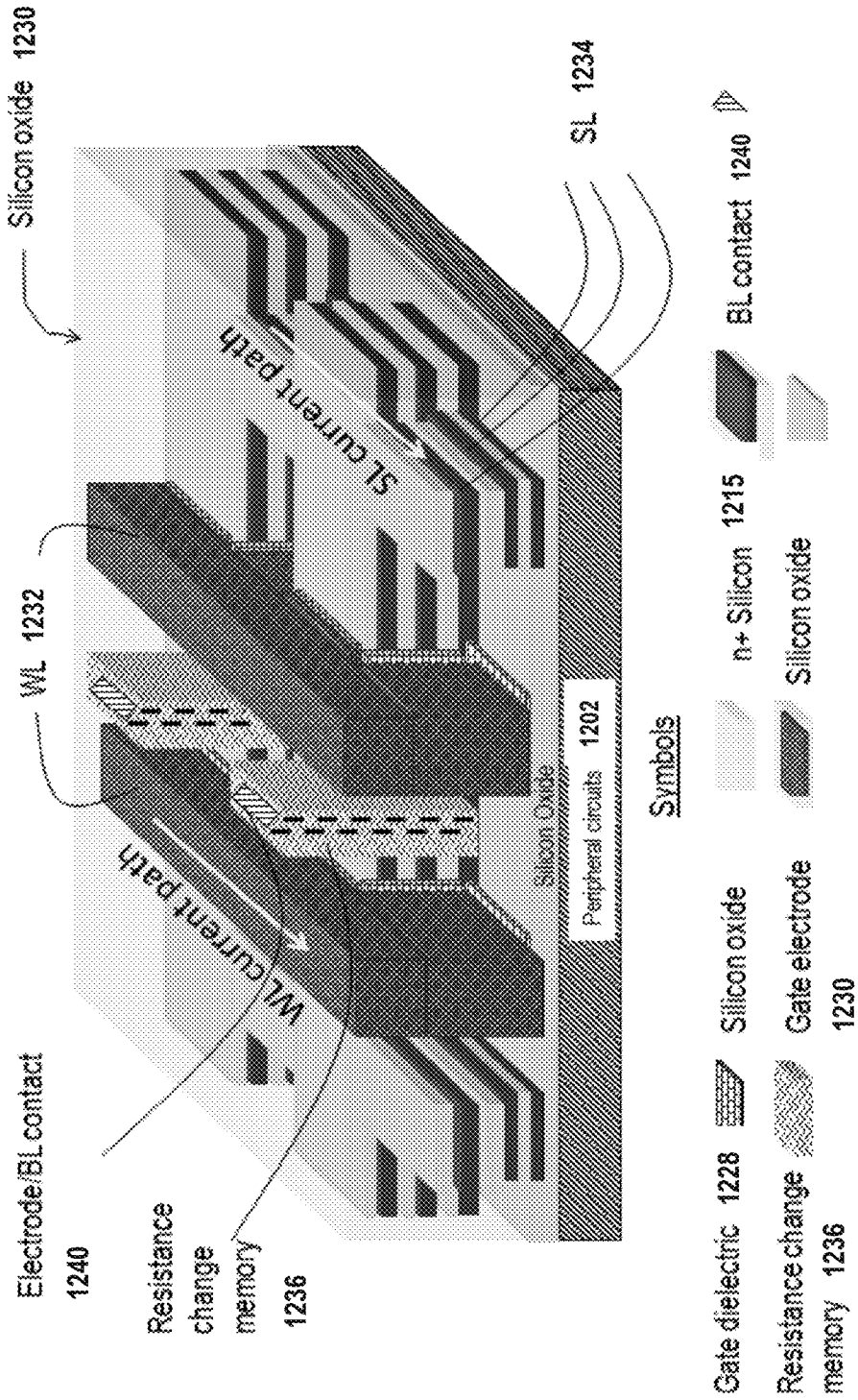


Fig. 12J

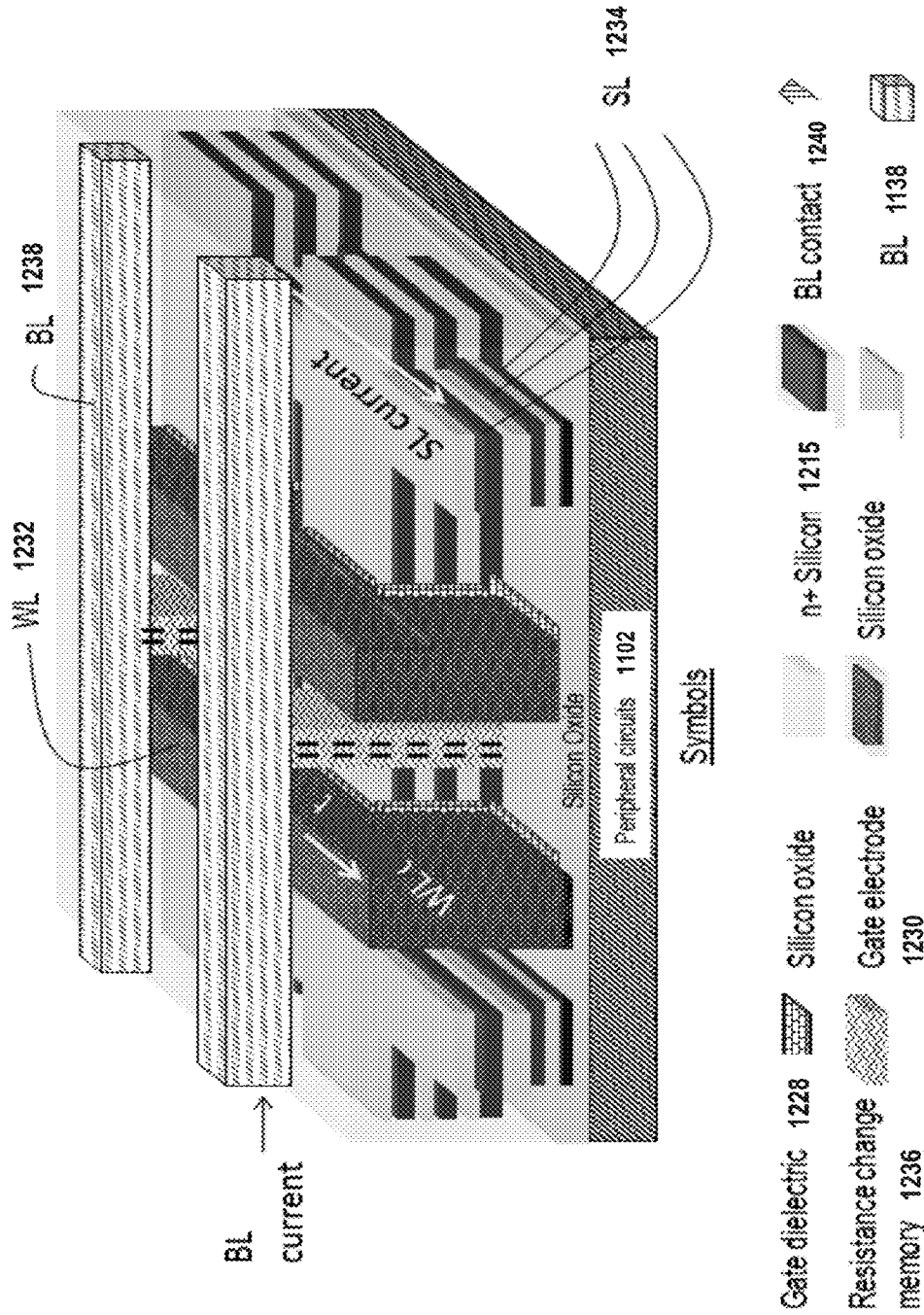
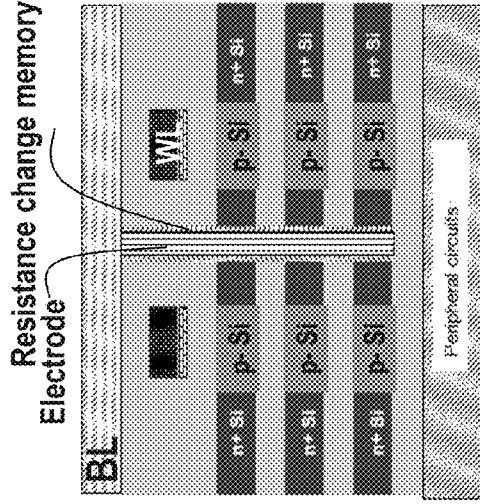
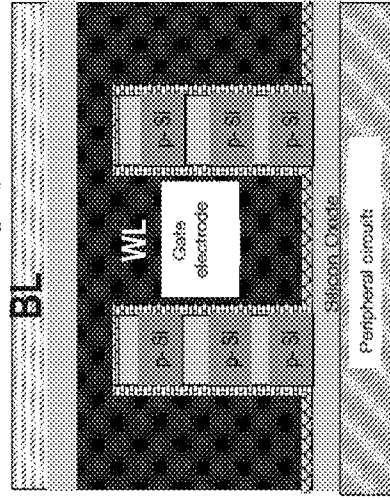


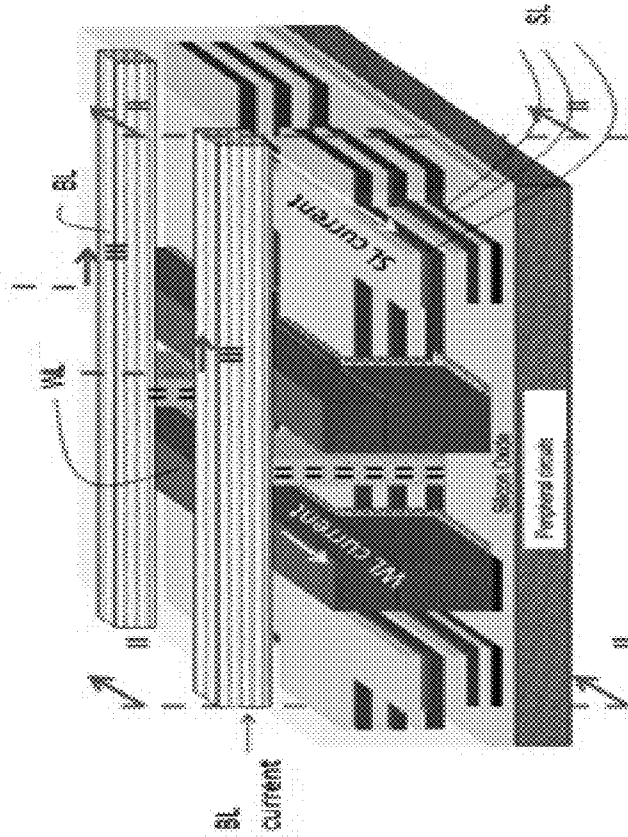
Fig. 12K



View along II plane



View along III plane



- Gate dielectric 1228
- Resistance change memory 1236
- n+ Silicon 1215
- Silicon oxide
- Silicon oxide
- Gate electrode 1230
- BL contact 1240
- BL 1238

Fig. 12L

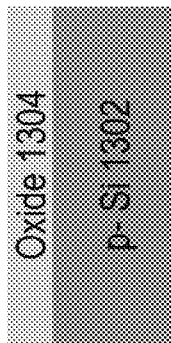


Fig. 13A

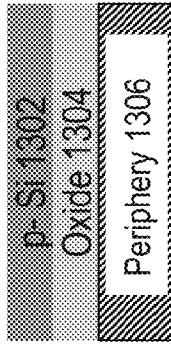


Fig. 13B

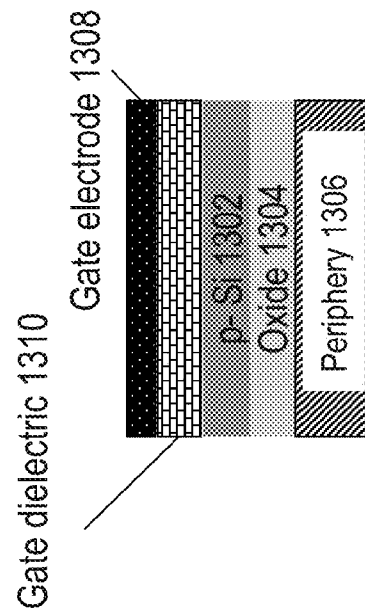


Fig. 13C

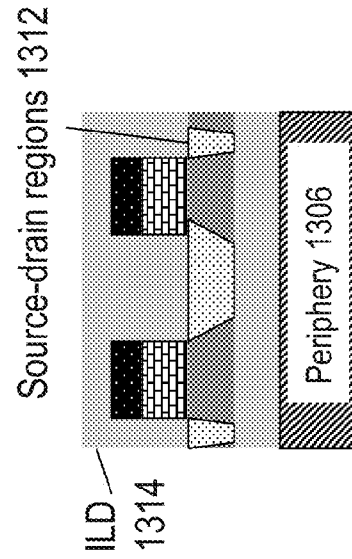


Fig. 13D

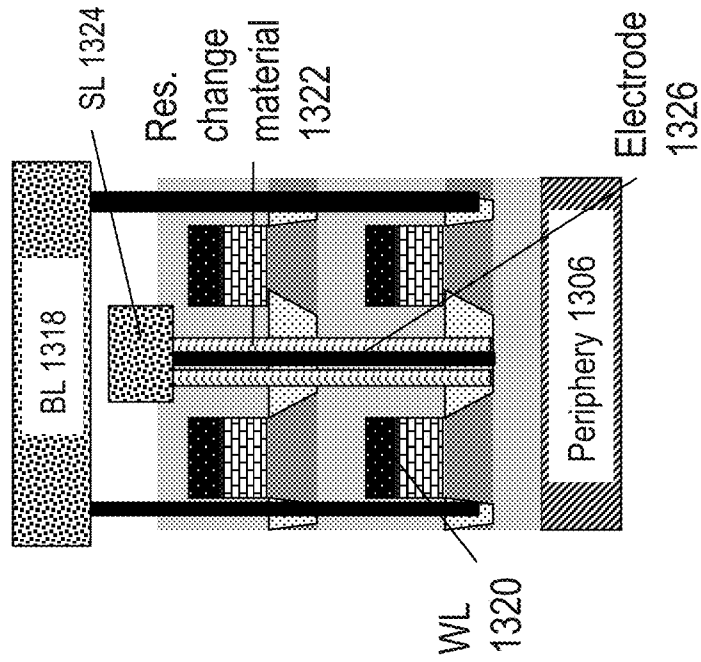


Fig. 13F

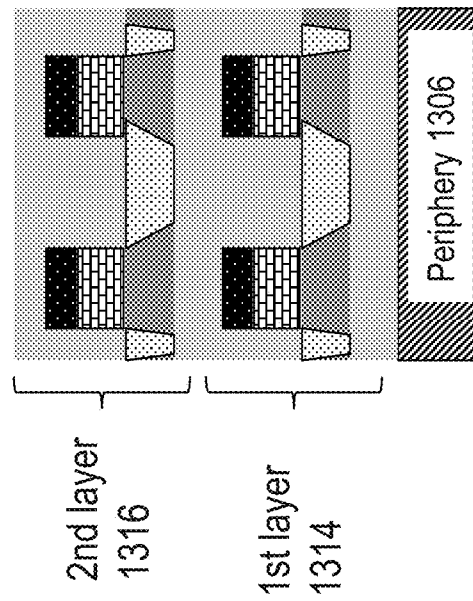


Fig. 13E

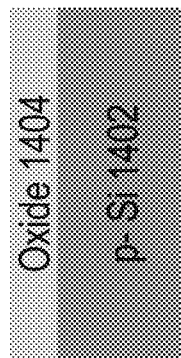


Fig. 14A

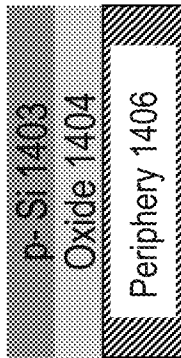


Fig. 14B

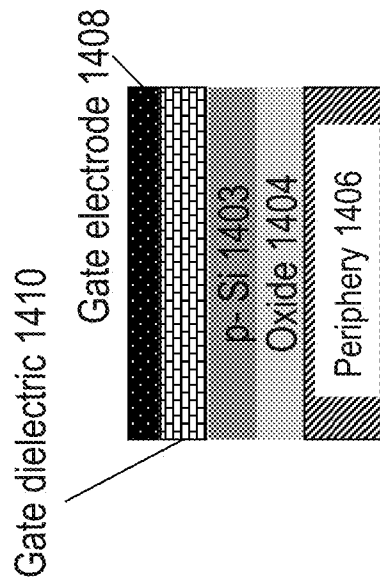


Fig. 14C

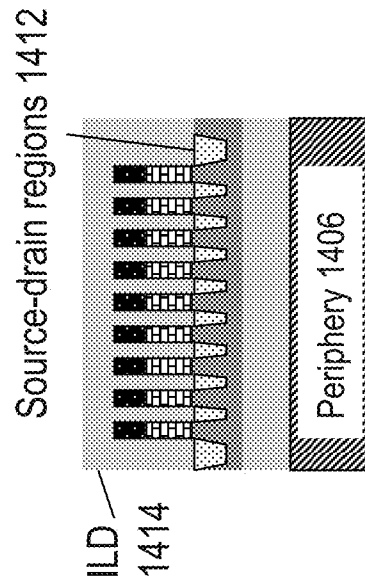


Fig. 14D

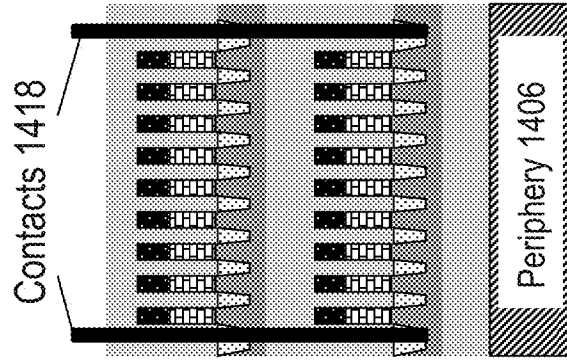


Fig. 14F

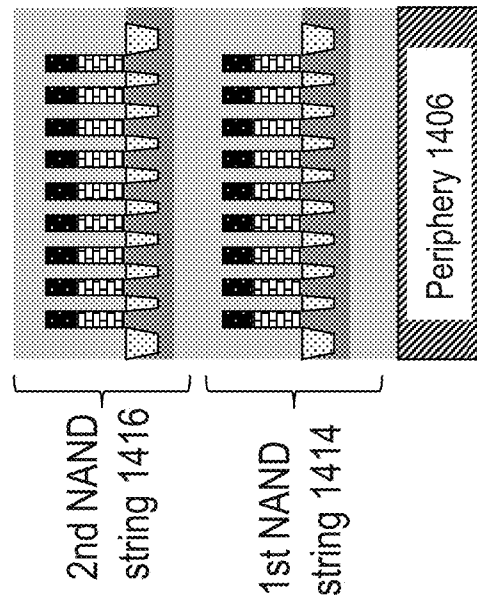


Fig. 14E

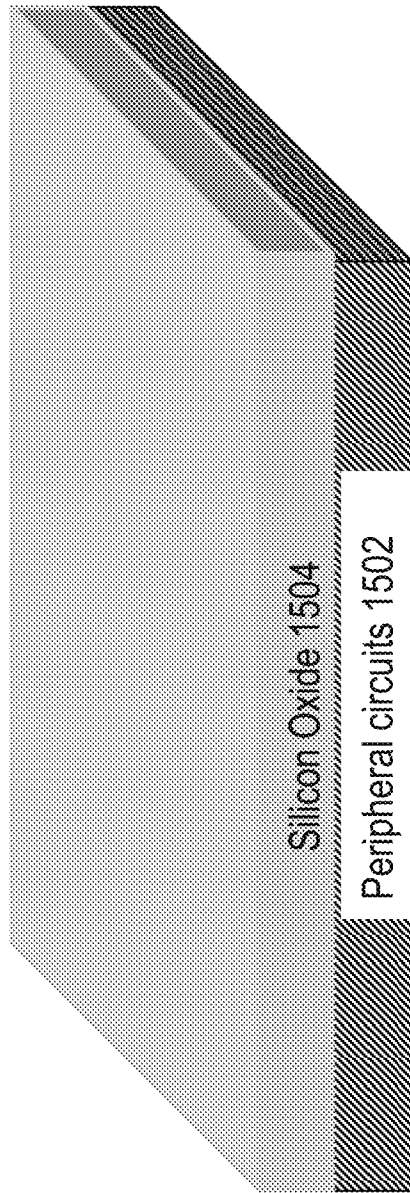


Fig. 15A

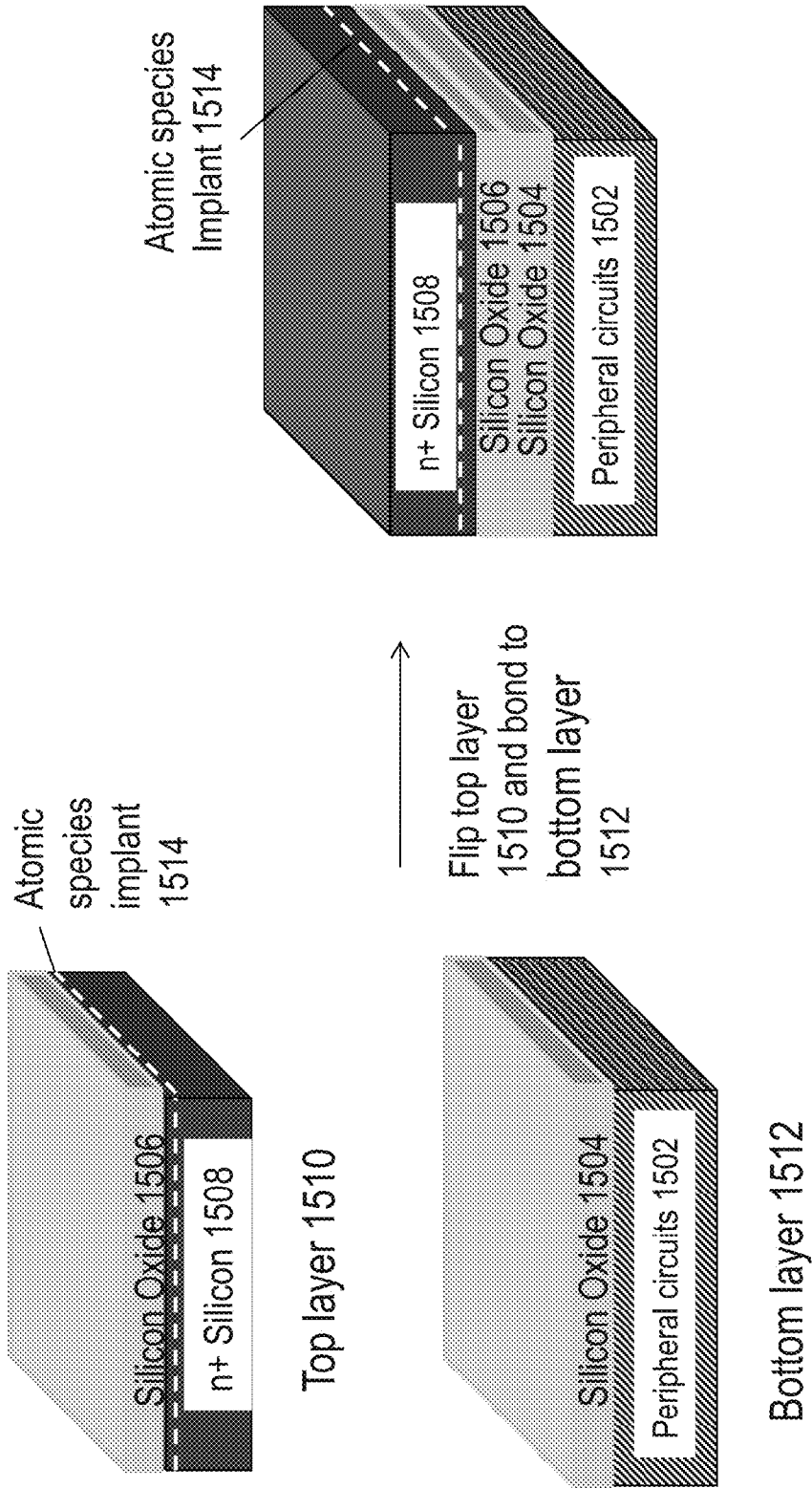


Fig. 15B

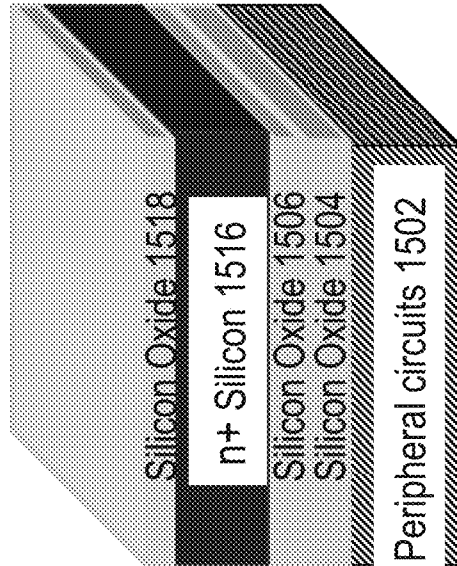


Fig. 15C

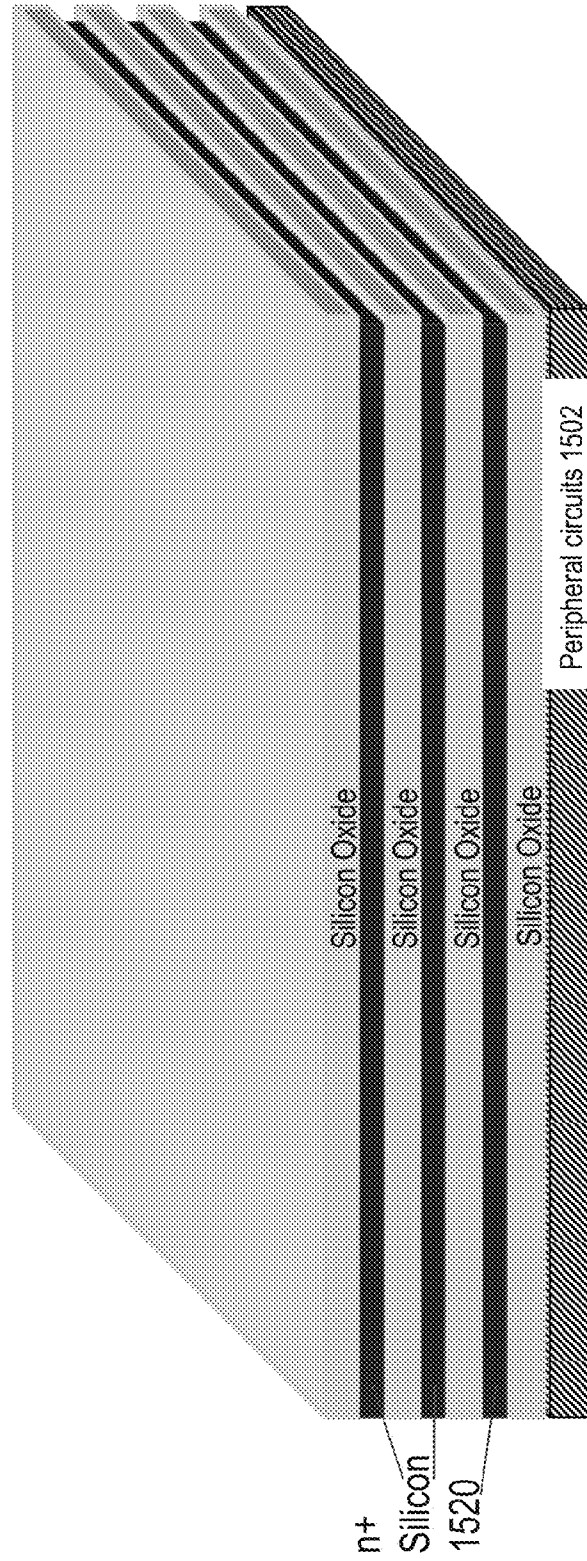


Fig. 15D

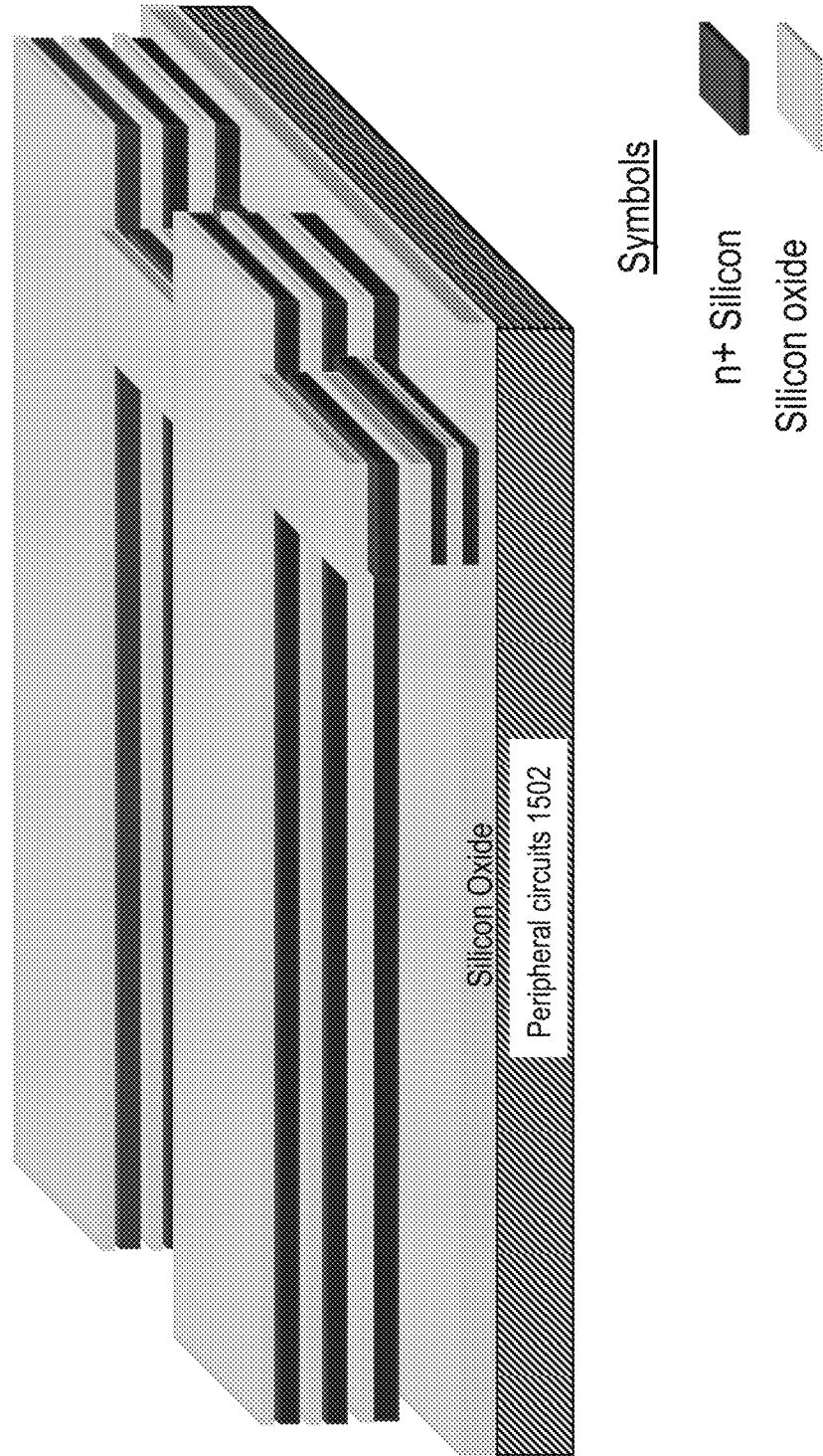


Fig. 15E

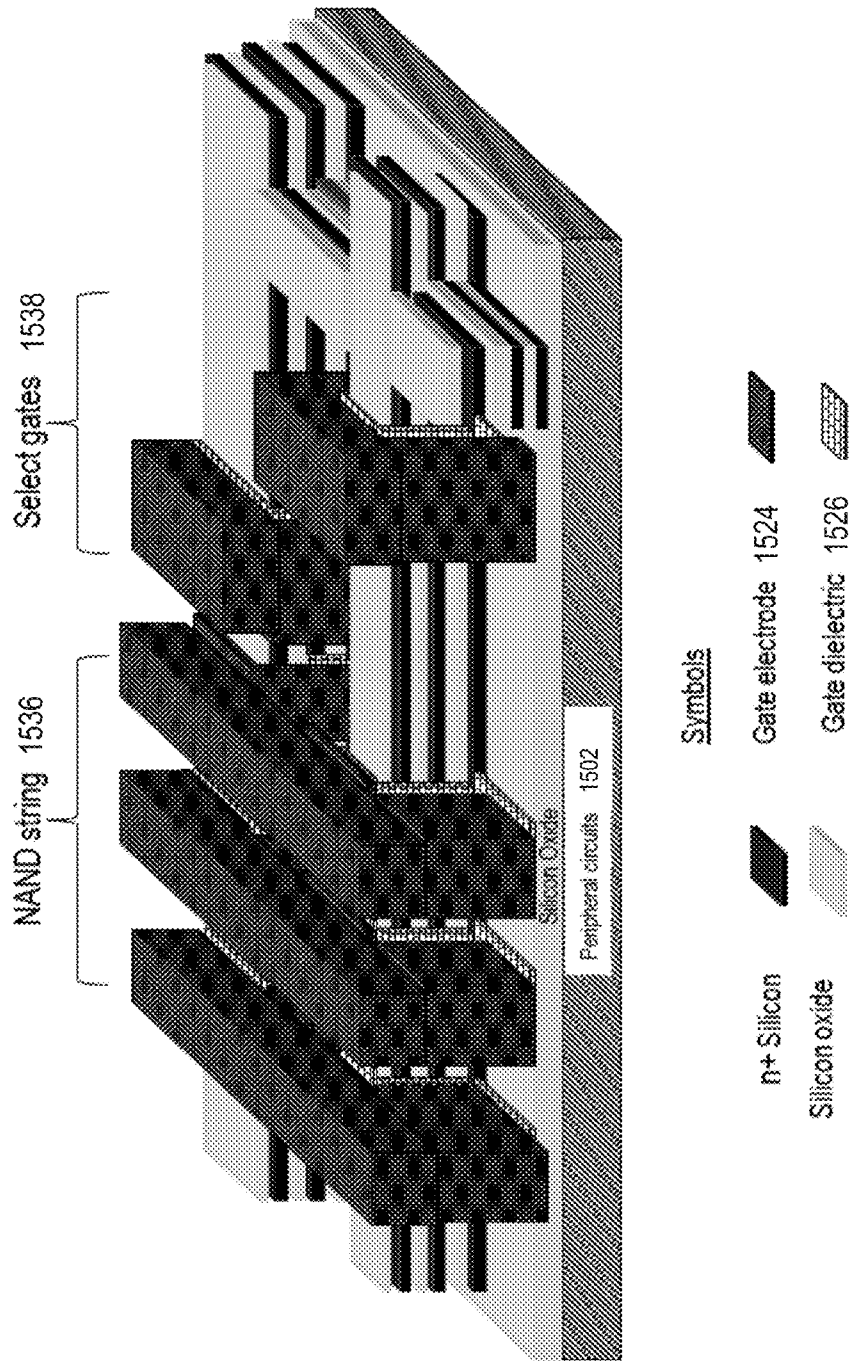


Fig. 15F

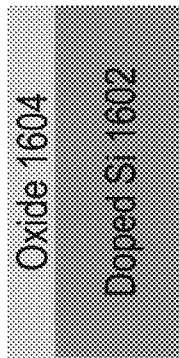


Fig. 16A

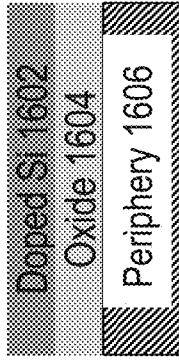


Fig. 16B

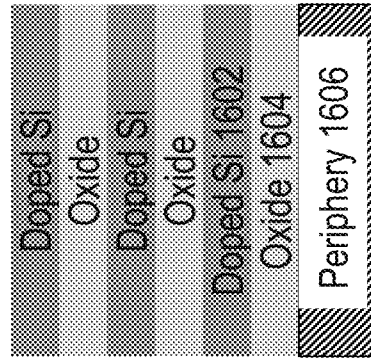
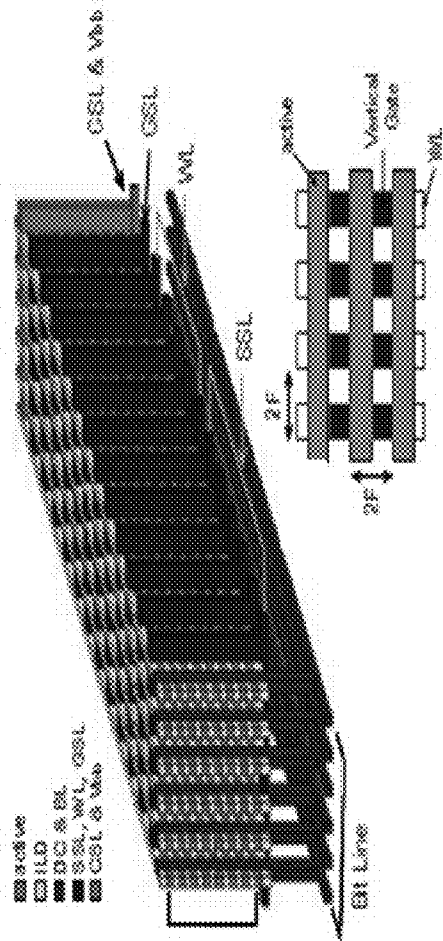
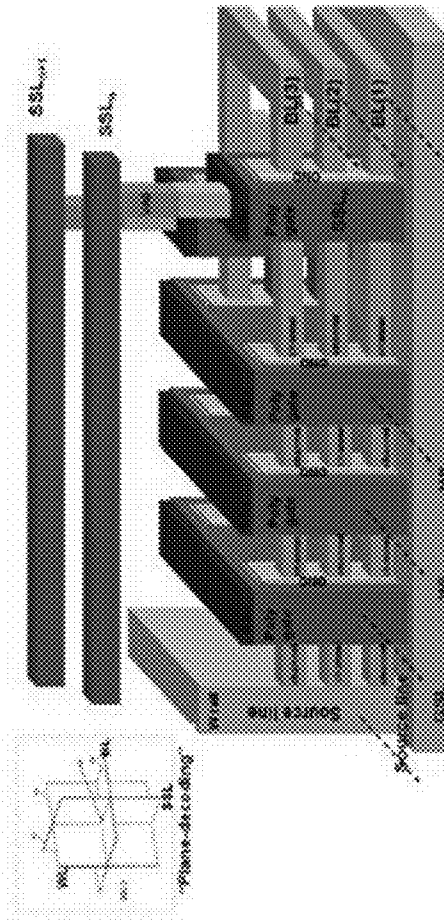


Fig. 16C



Architecture from "Multi-layered Vertical Gate NAND Flash overcoming stacking limit for terabit density storage", Symposium on VLSI Technology, 2009 by W. Kim, S. Choi, et al.



Architecture from "A Highly Scalable 8-Layer 3D Vertical-Gate (VG) TFT NAND Flash Using Junction-Free Buried Channel BE-SONOS Device," Symposium on VLSI Technology, 2010 by Hang-Ting Lue, et al.

Fig. 16D

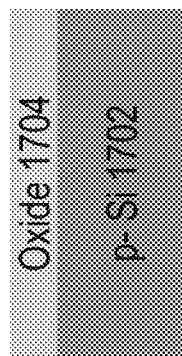


Fig. 17A

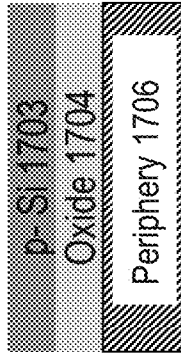


Fig. 17B

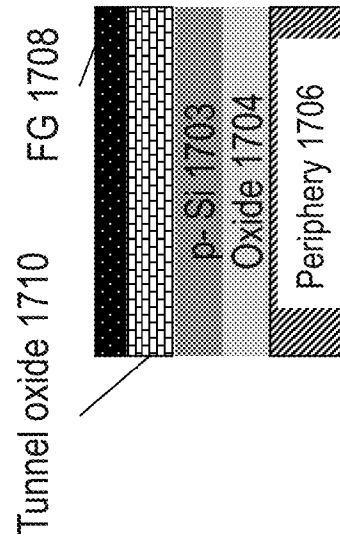


Fig. 17C

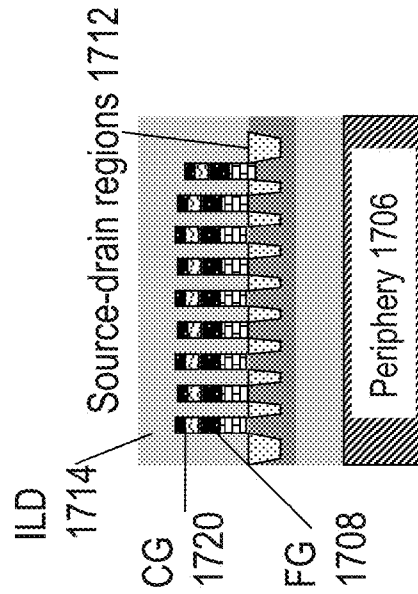


Fig. 17D

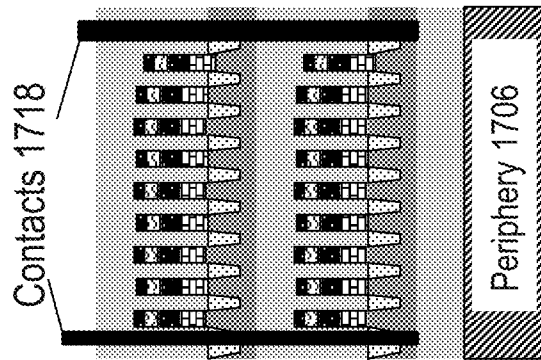


Fig. 17F

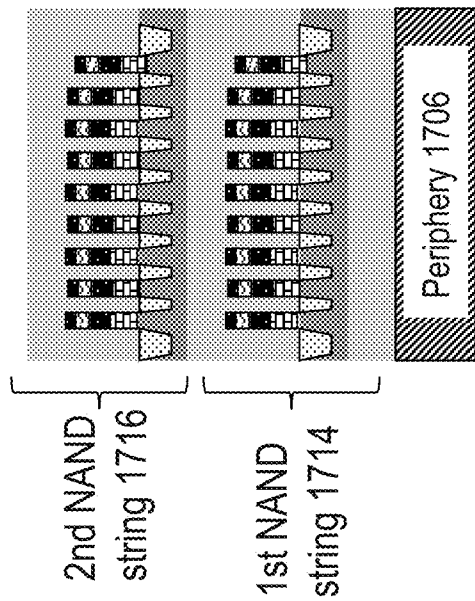


Fig. 17E

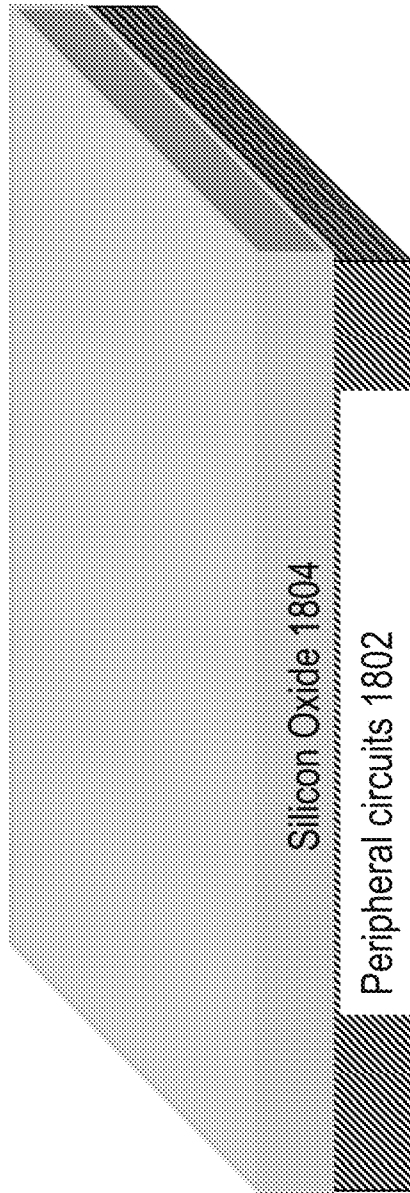


Fig. 18A

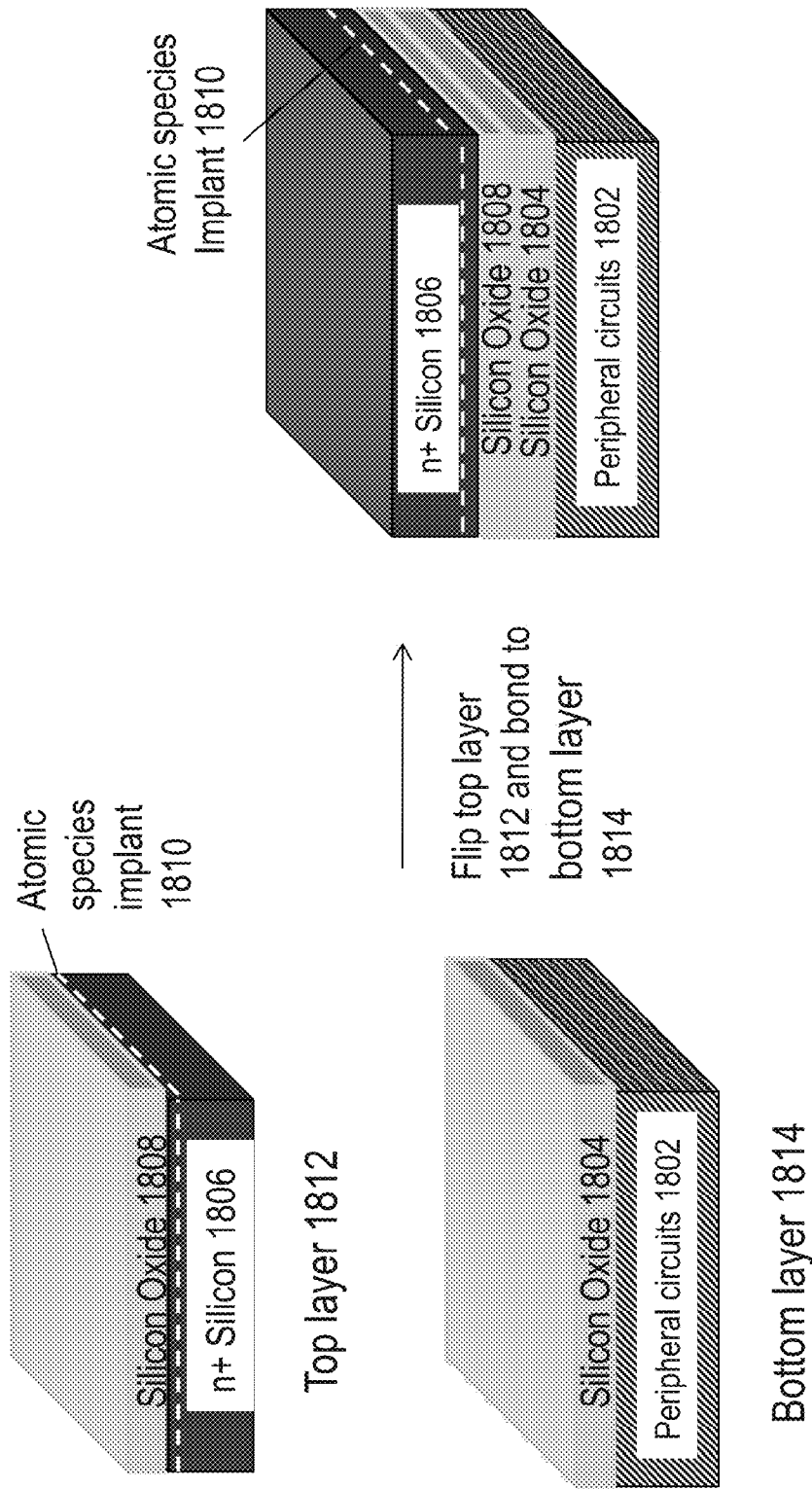


Fig. 18B

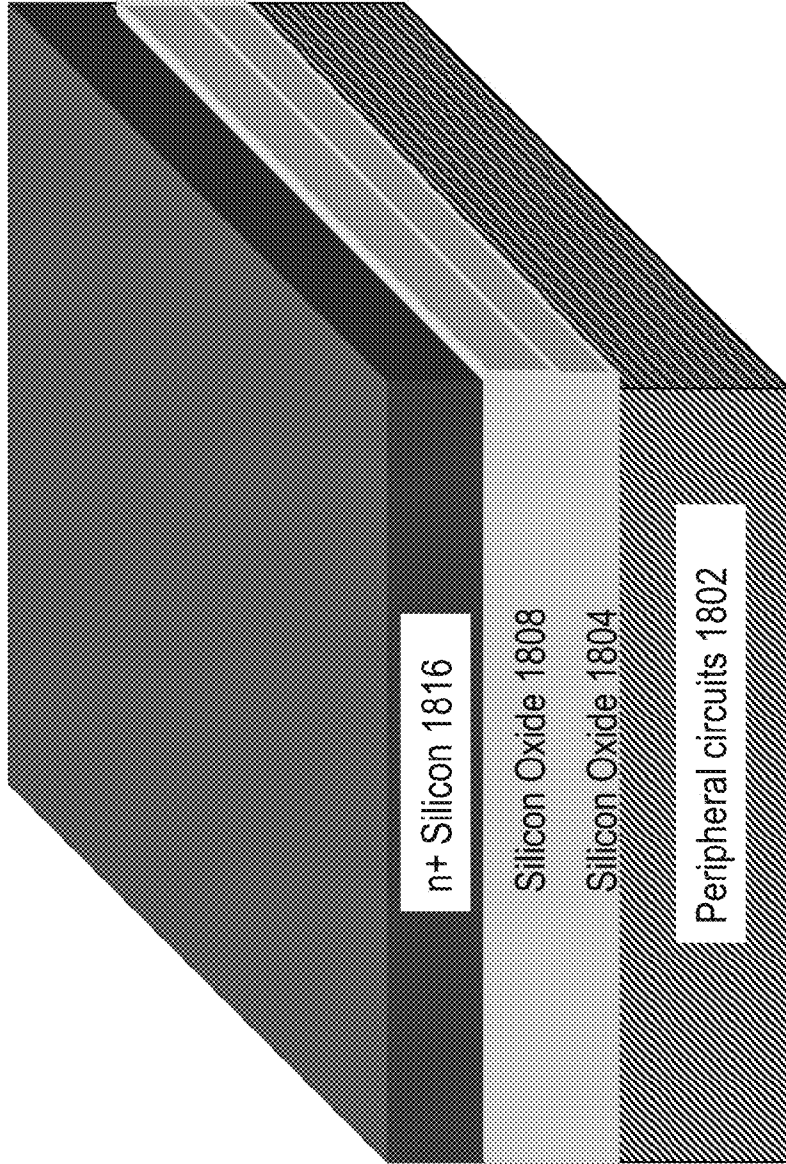


Fig. 18C

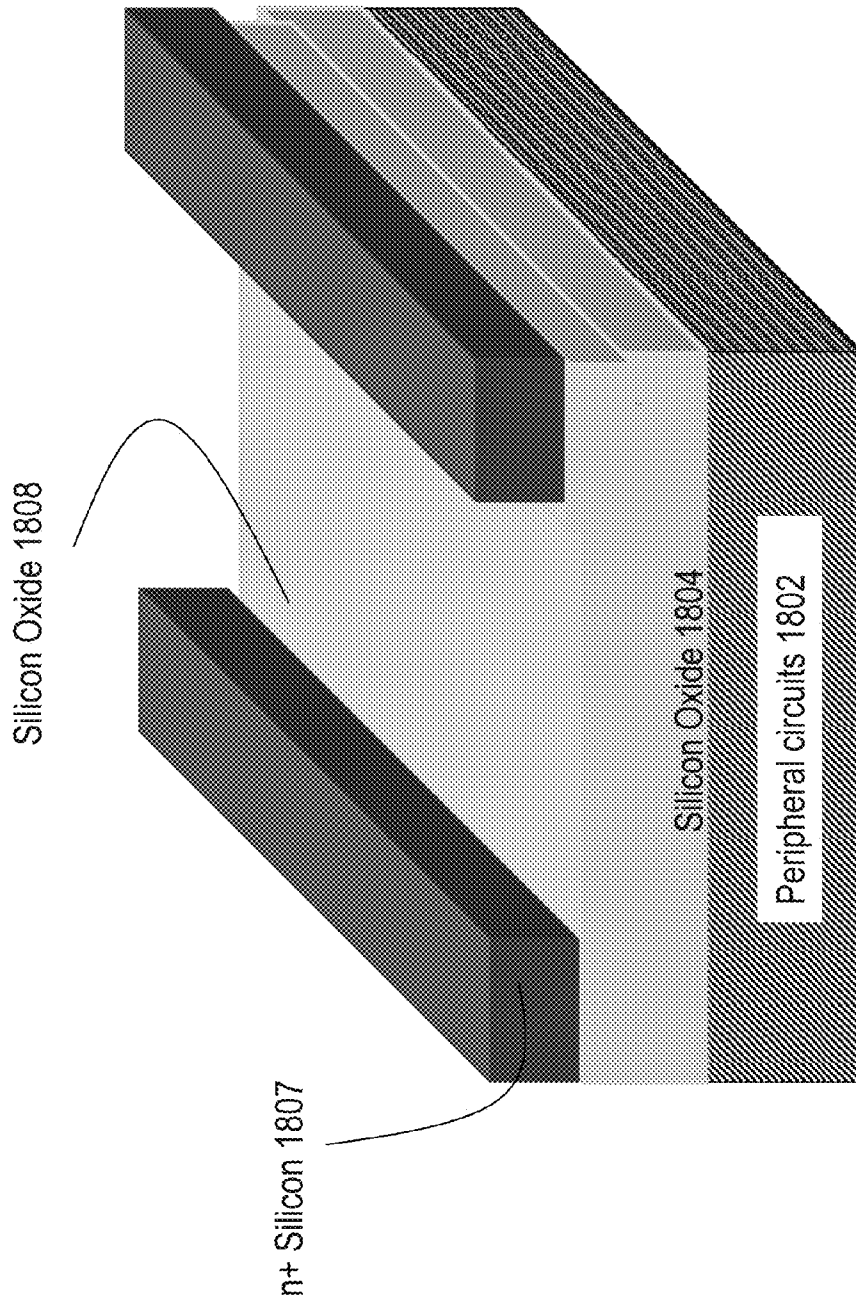


Fig. 18D

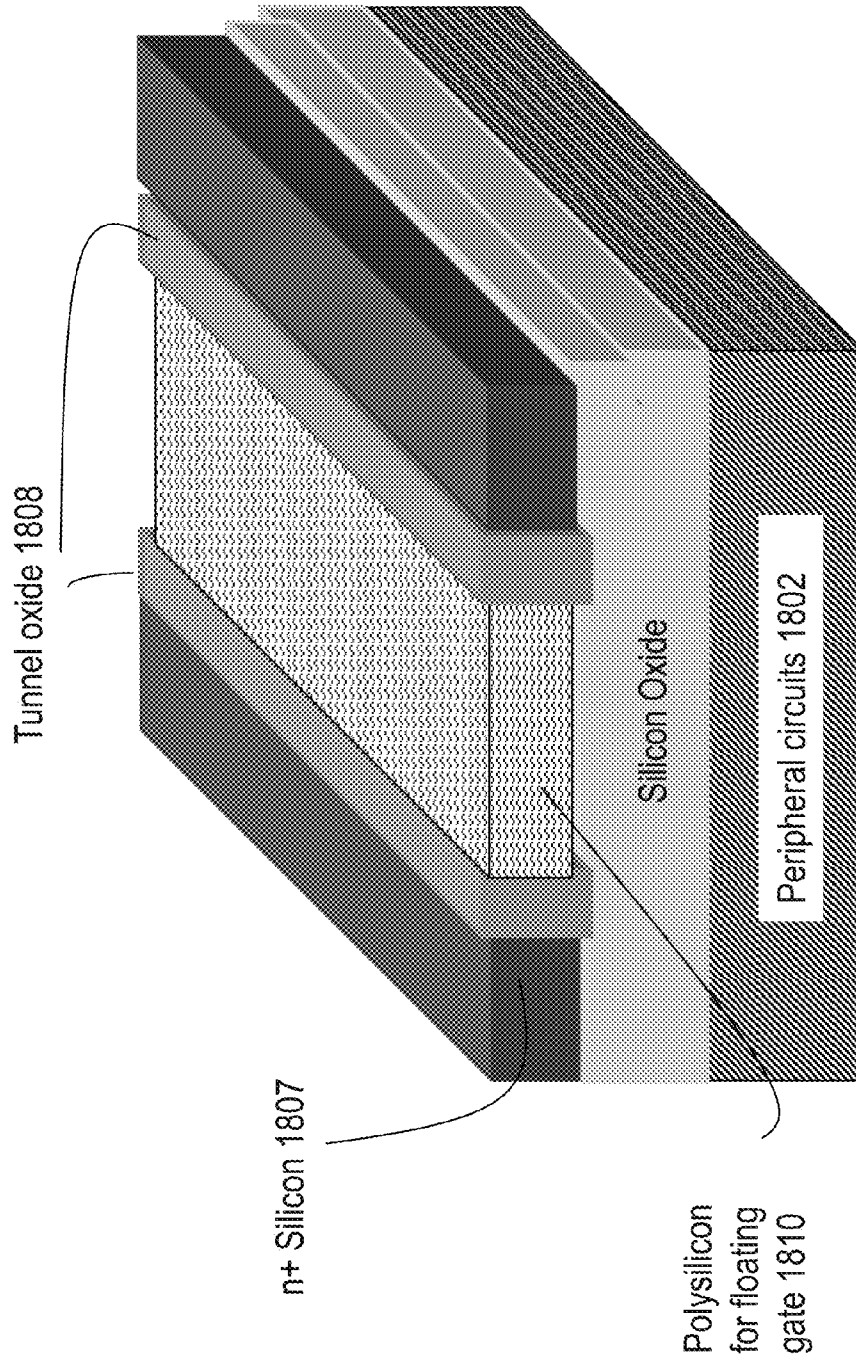


Fig. 18E

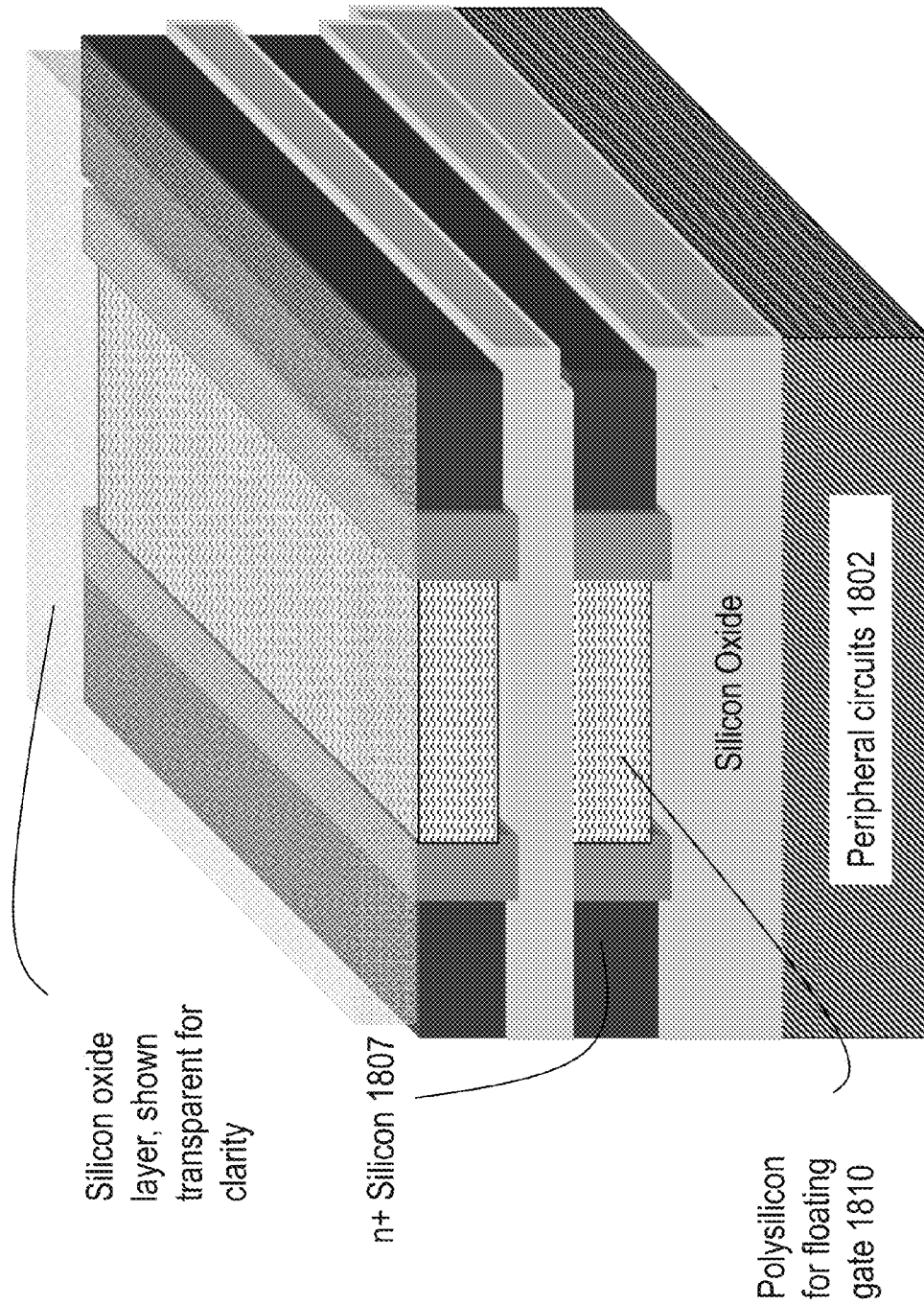


Fig. 18F

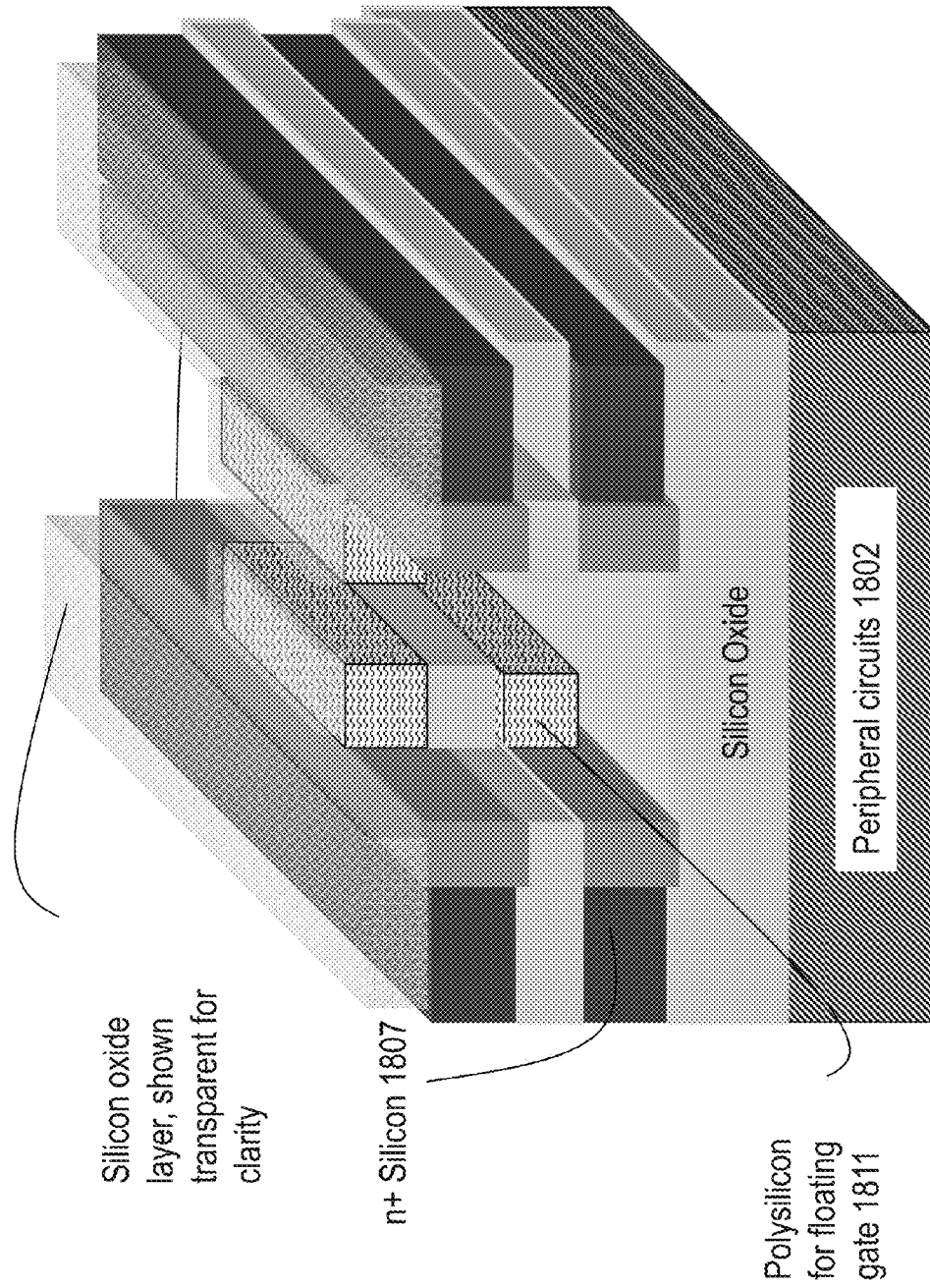


Fig. 18G

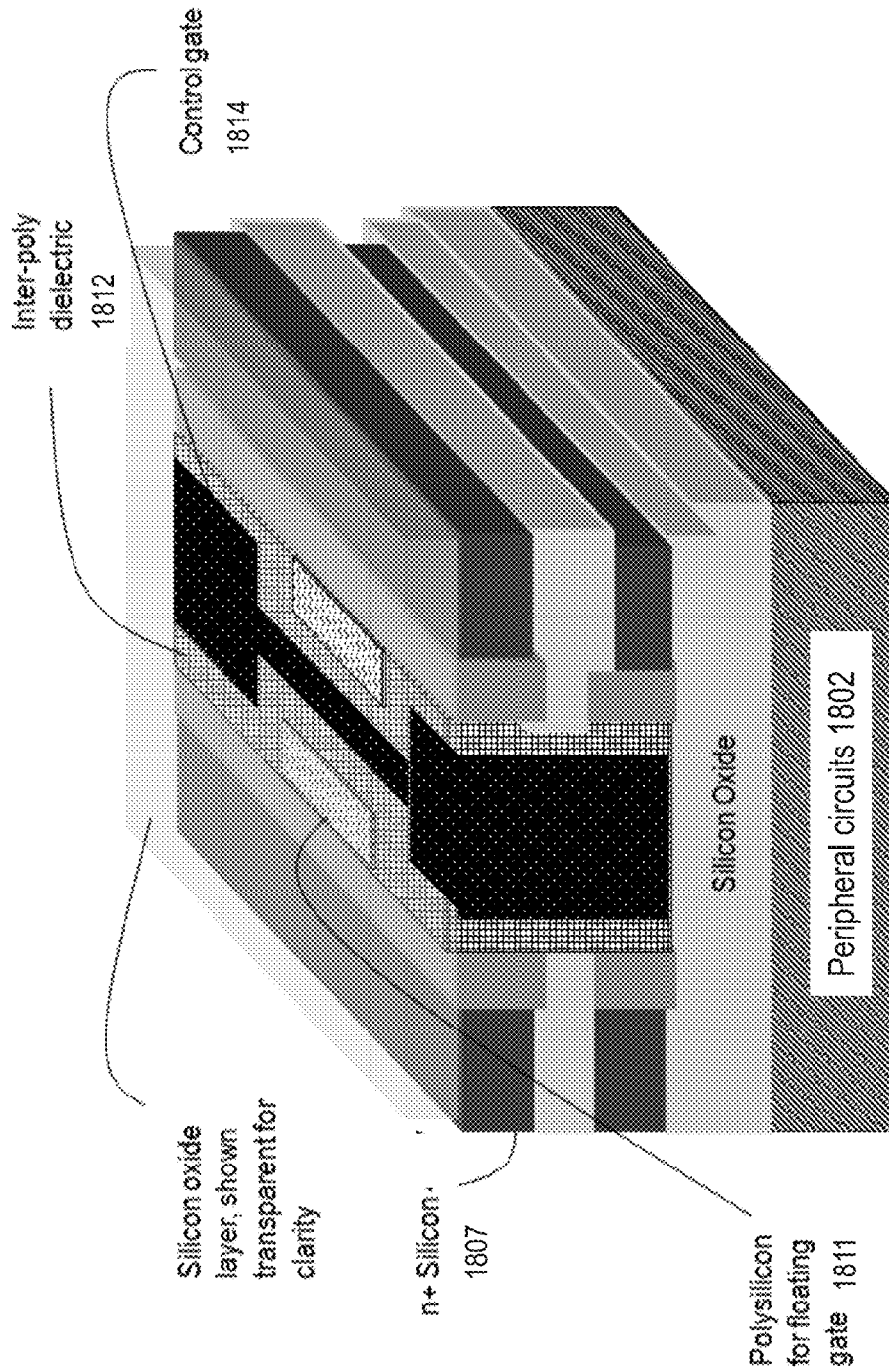


Fig. 18H

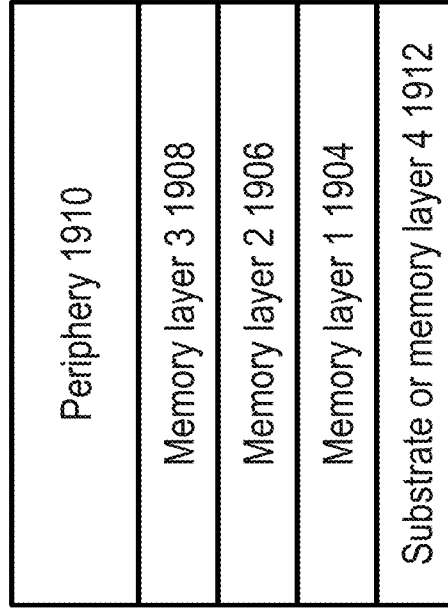


Fig. 19B: Periphery-on-top architecture
An alternative

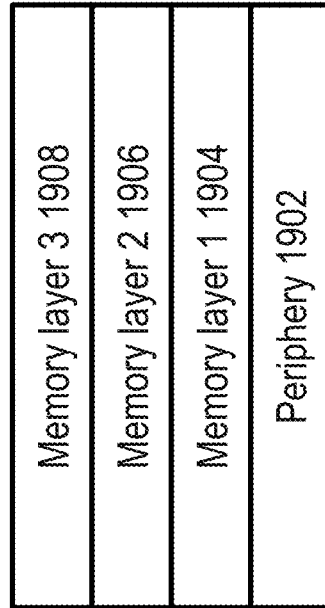


Fig. 19A: Periphery-on-bottom architecture
Used for Fig. 2-18

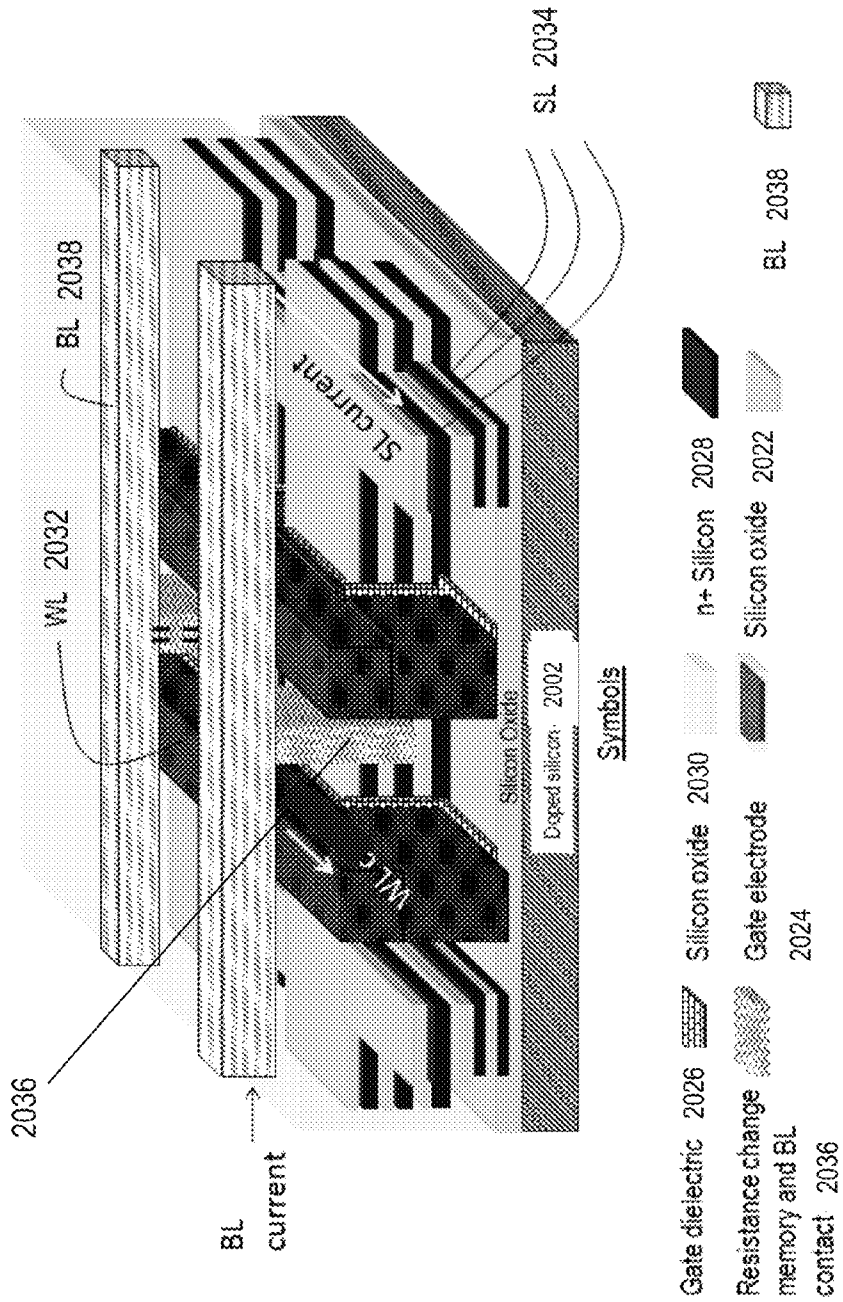


Fig. 20A

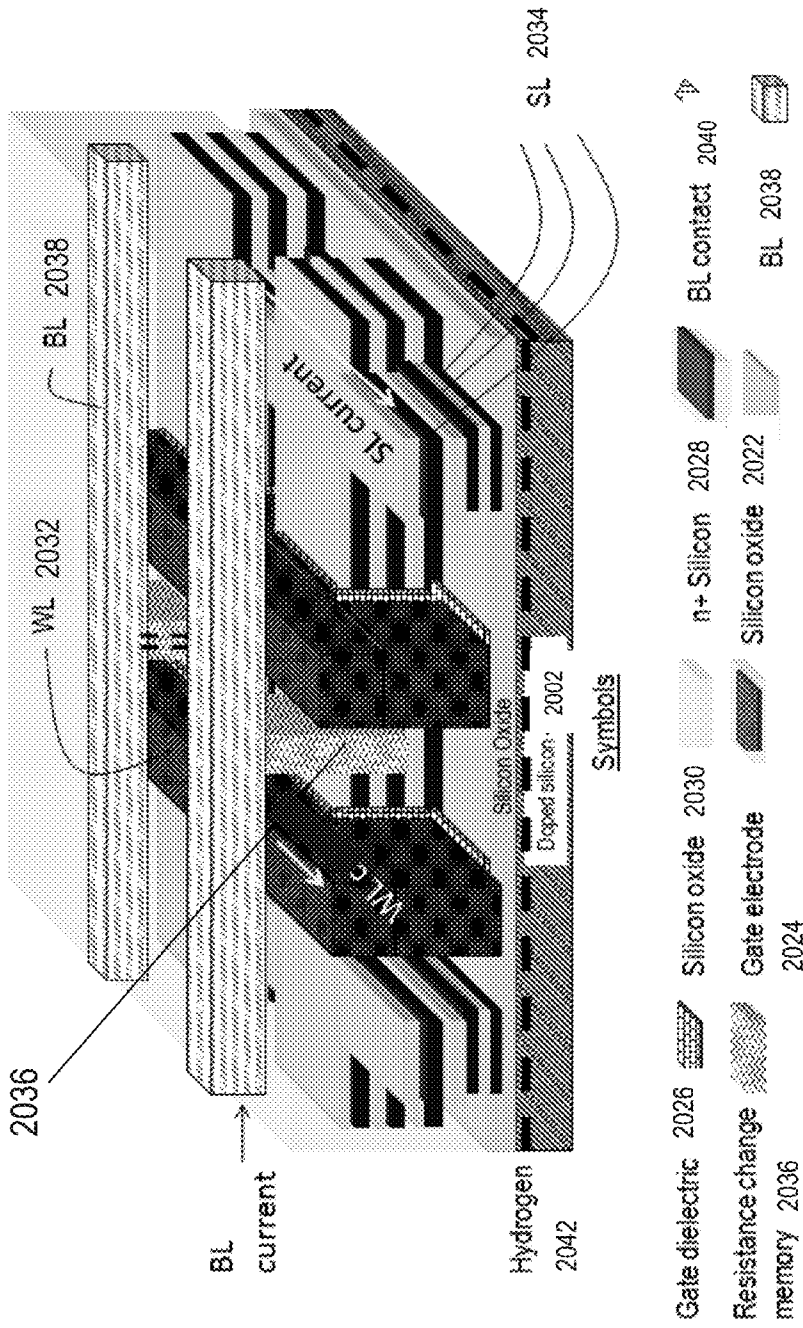


Fig. 20B

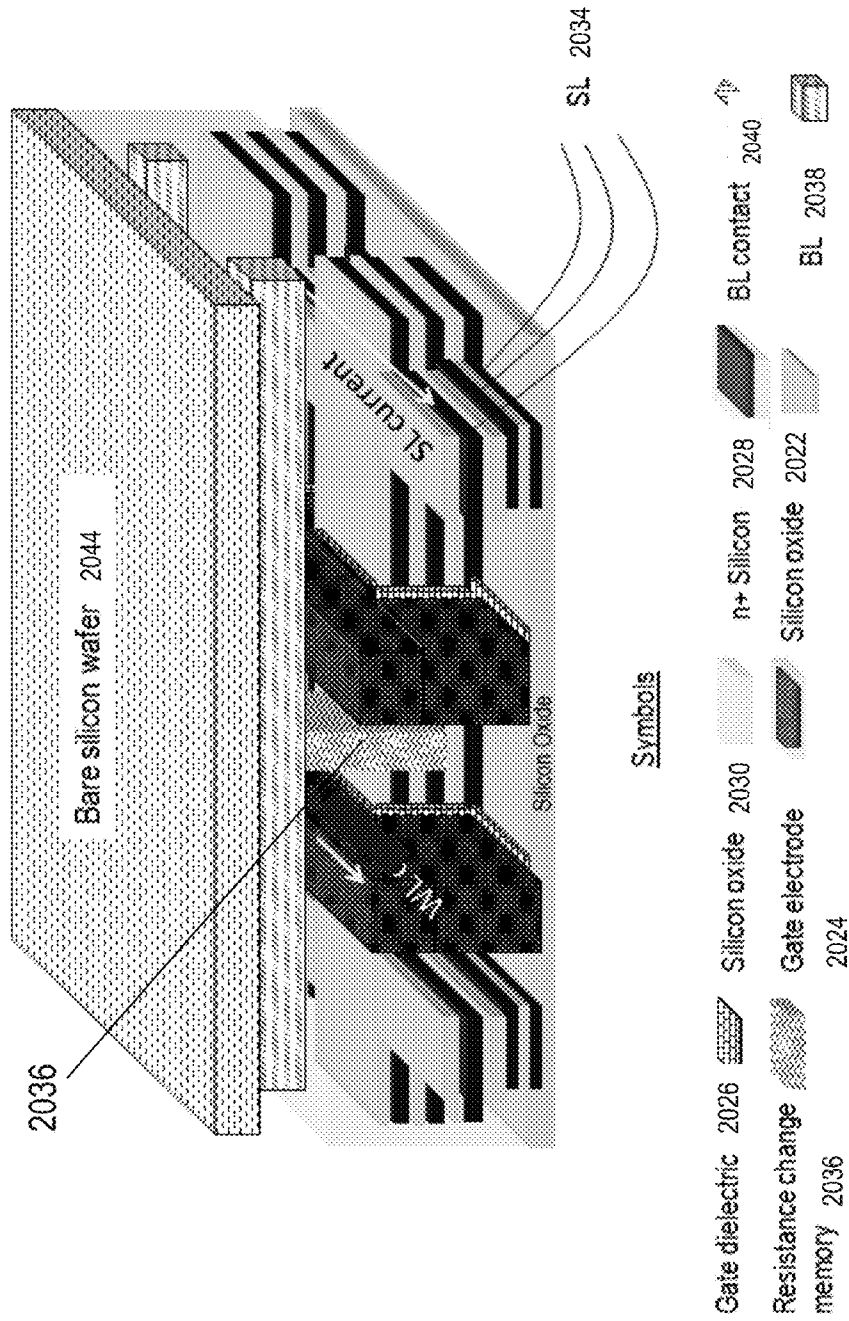


Fig. 20C

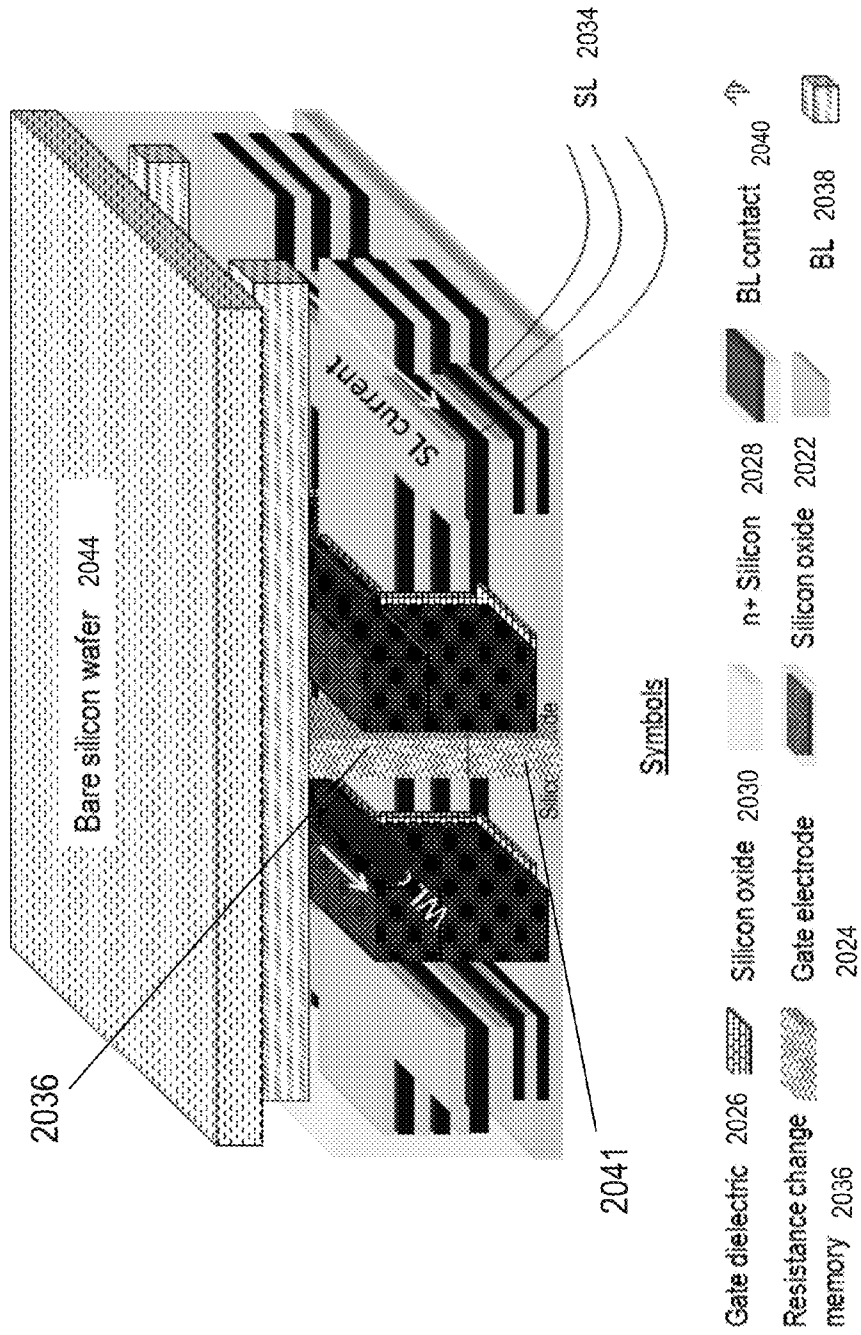


Fig. 20D

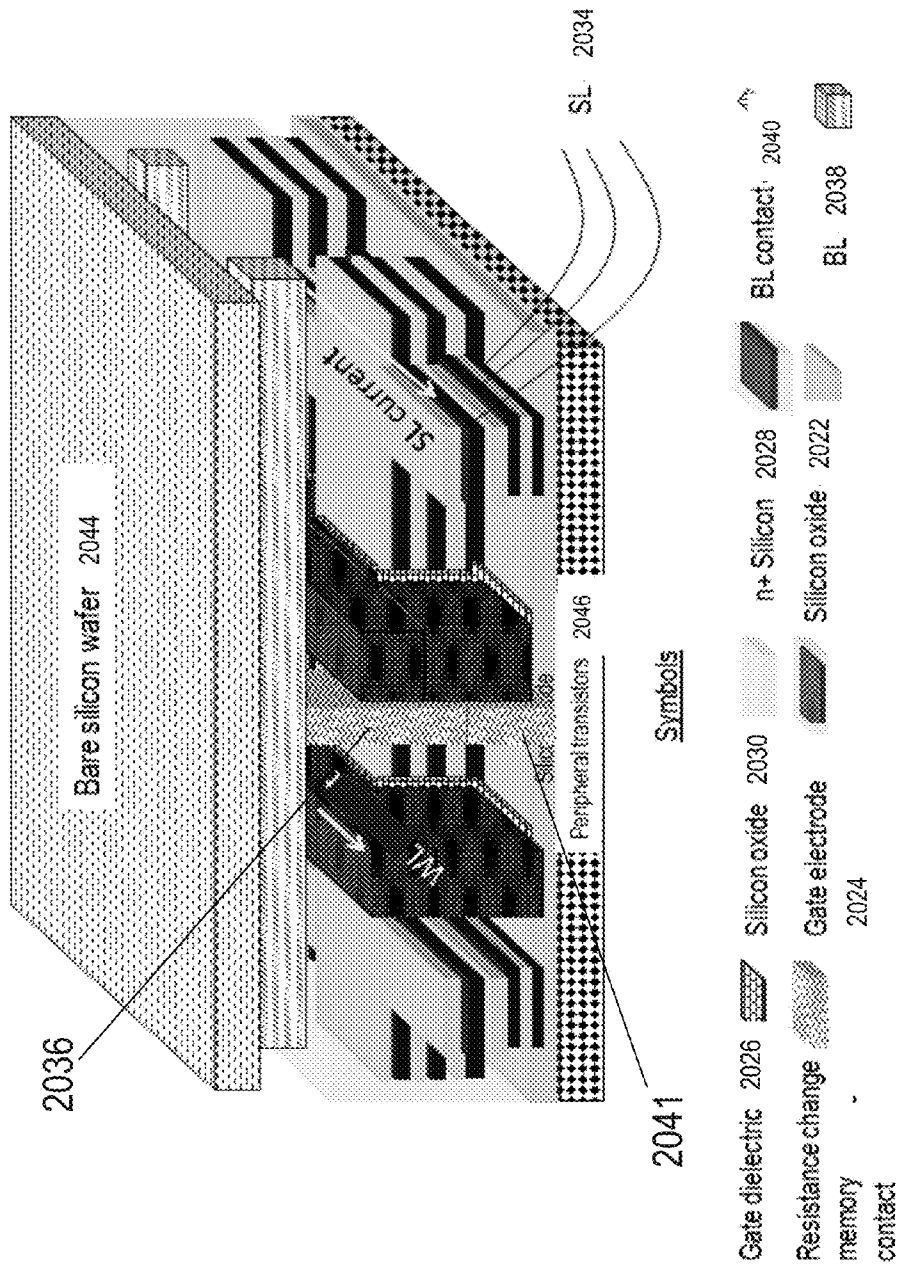


Fig. 20E

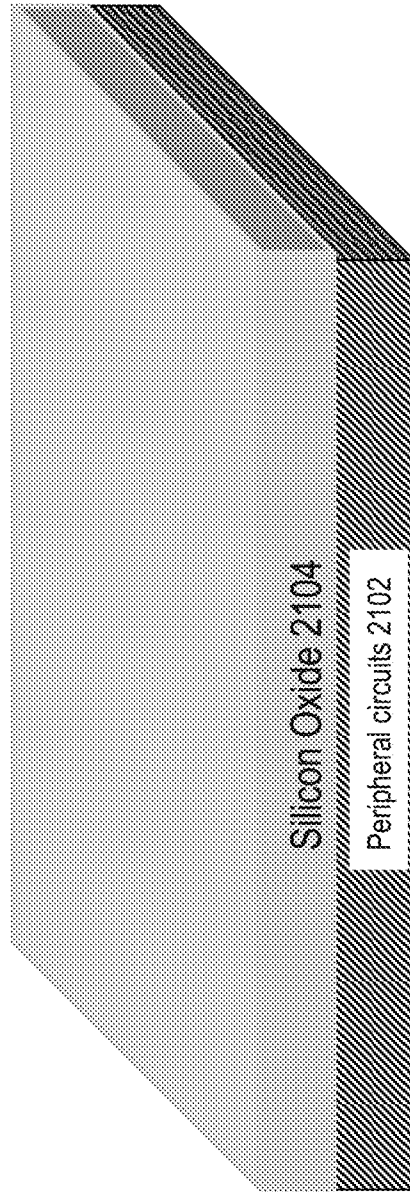


Fig. 21A

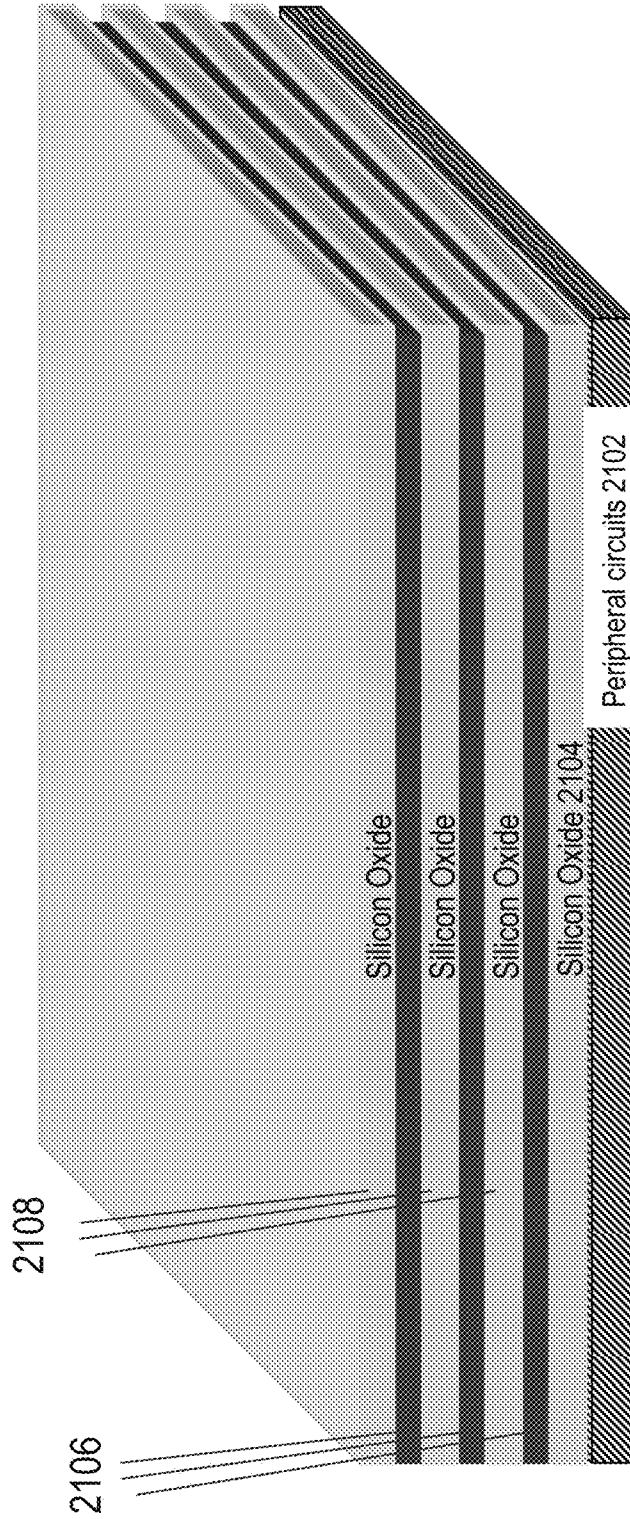


Fig. 21B

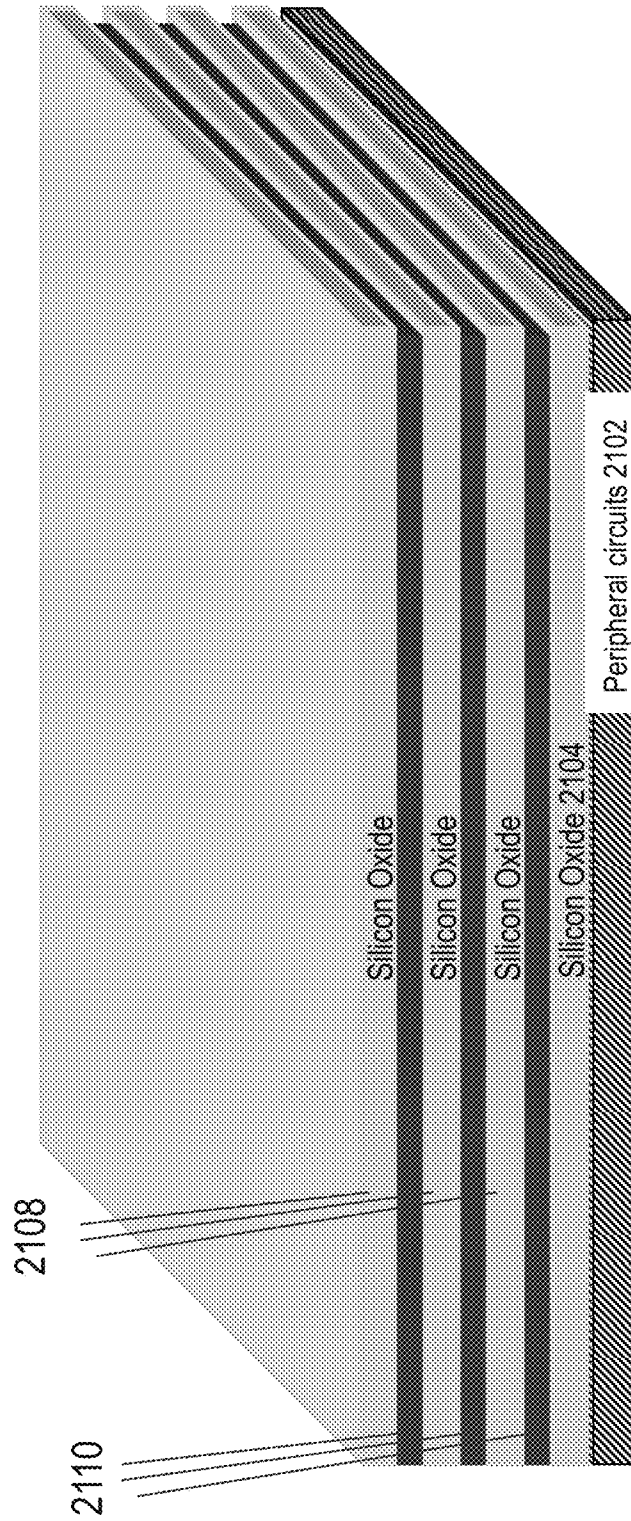


Fig. 21C

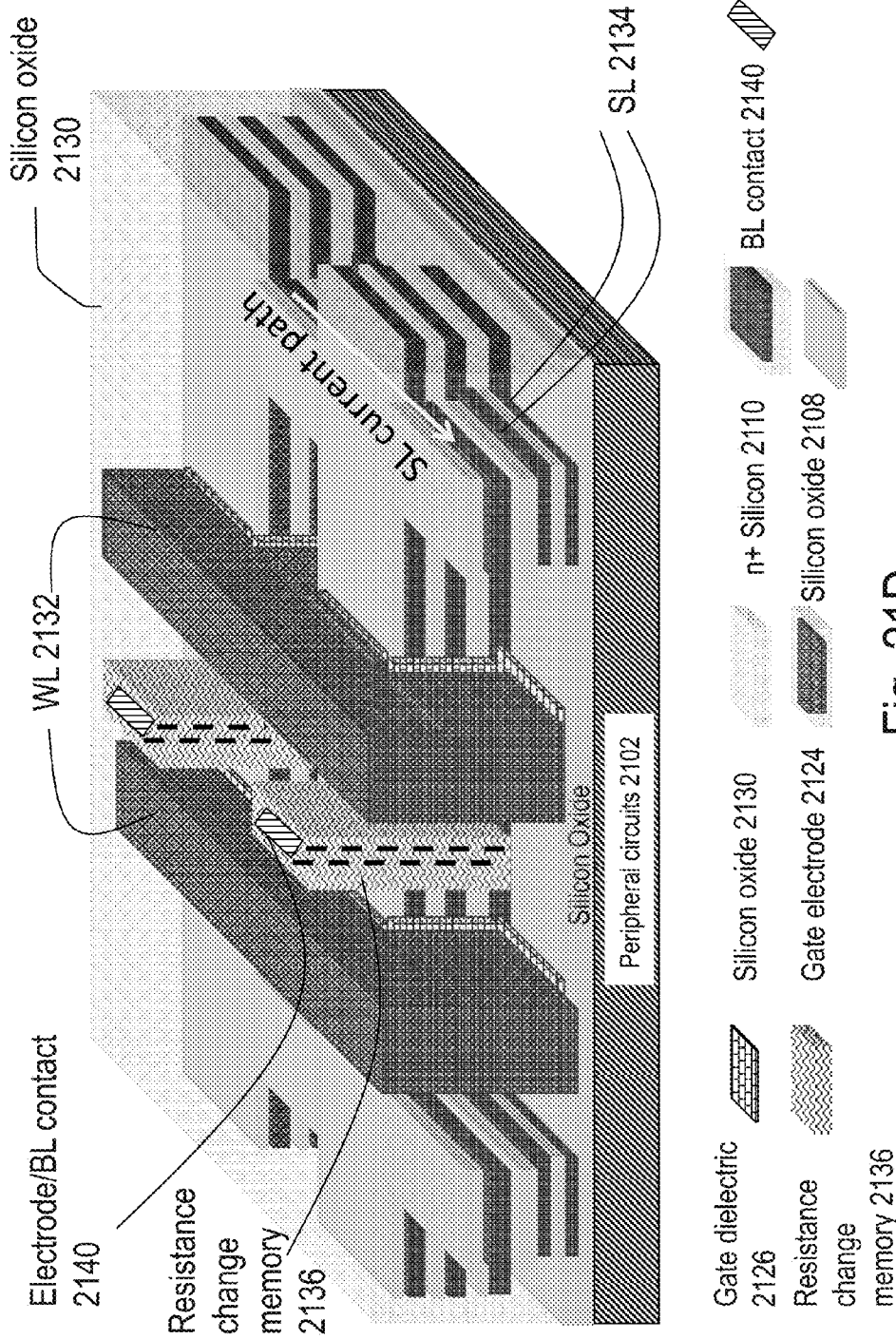


Fig. 21D

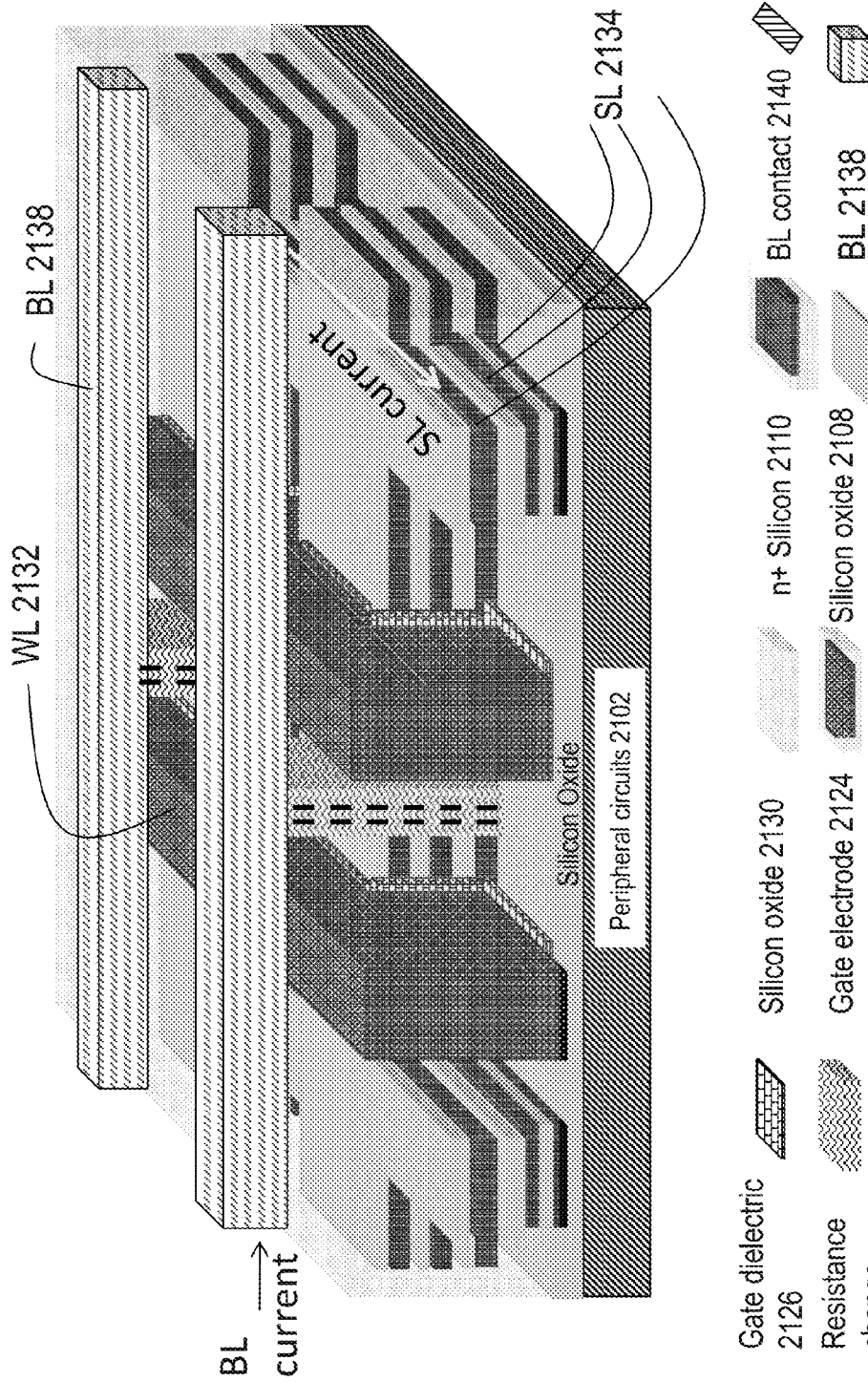


Fig. 21E

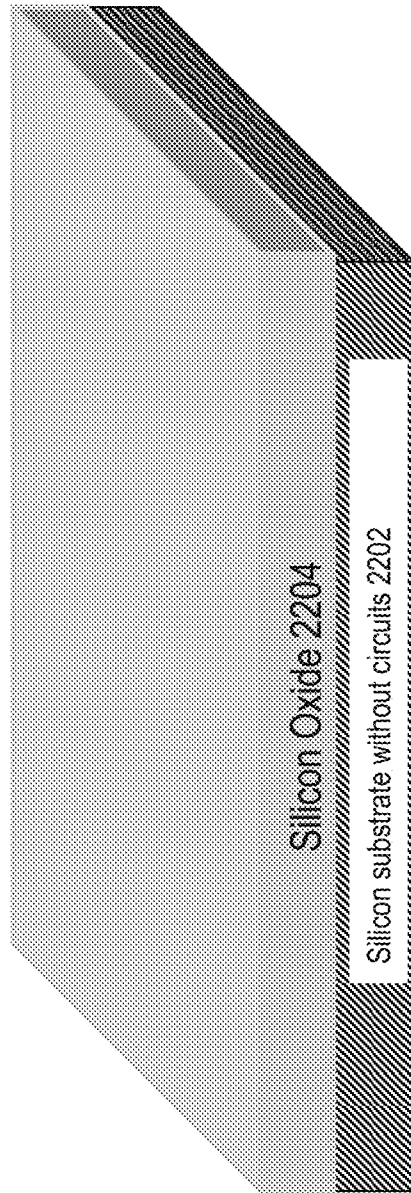


Fig. 22A

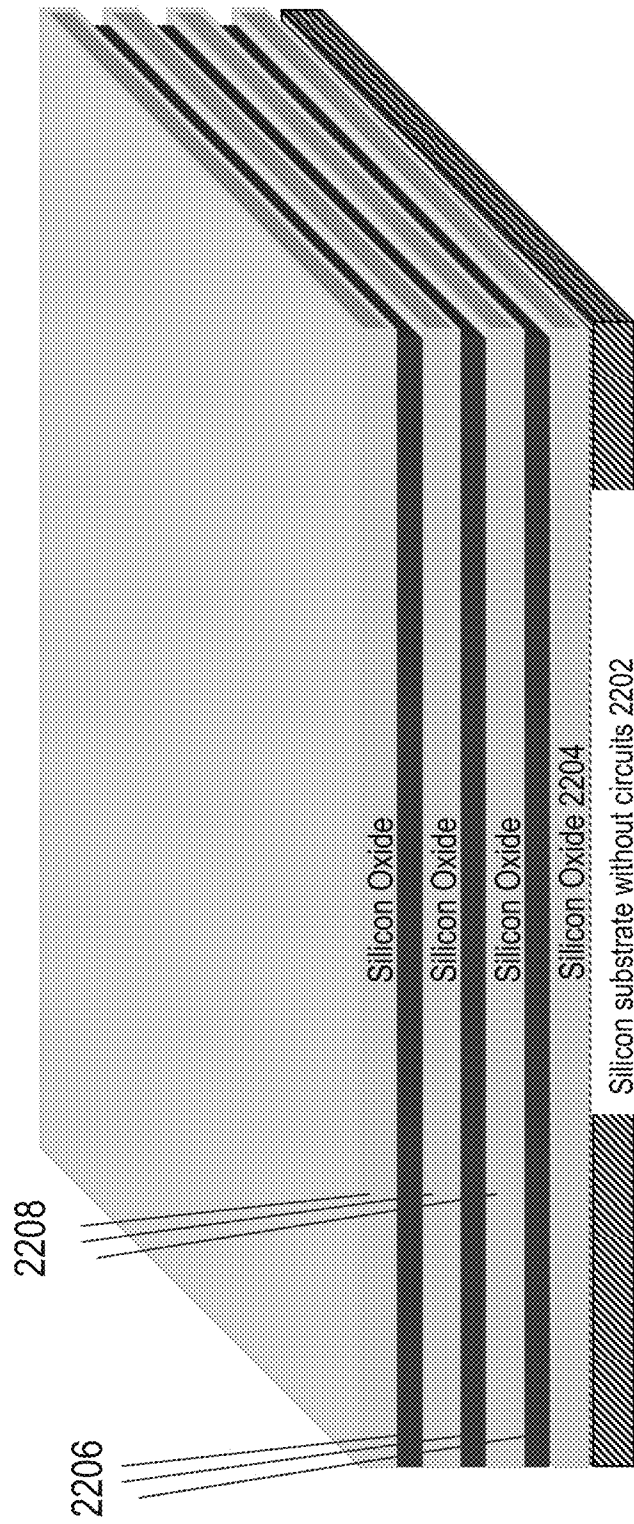


Fig. 22B

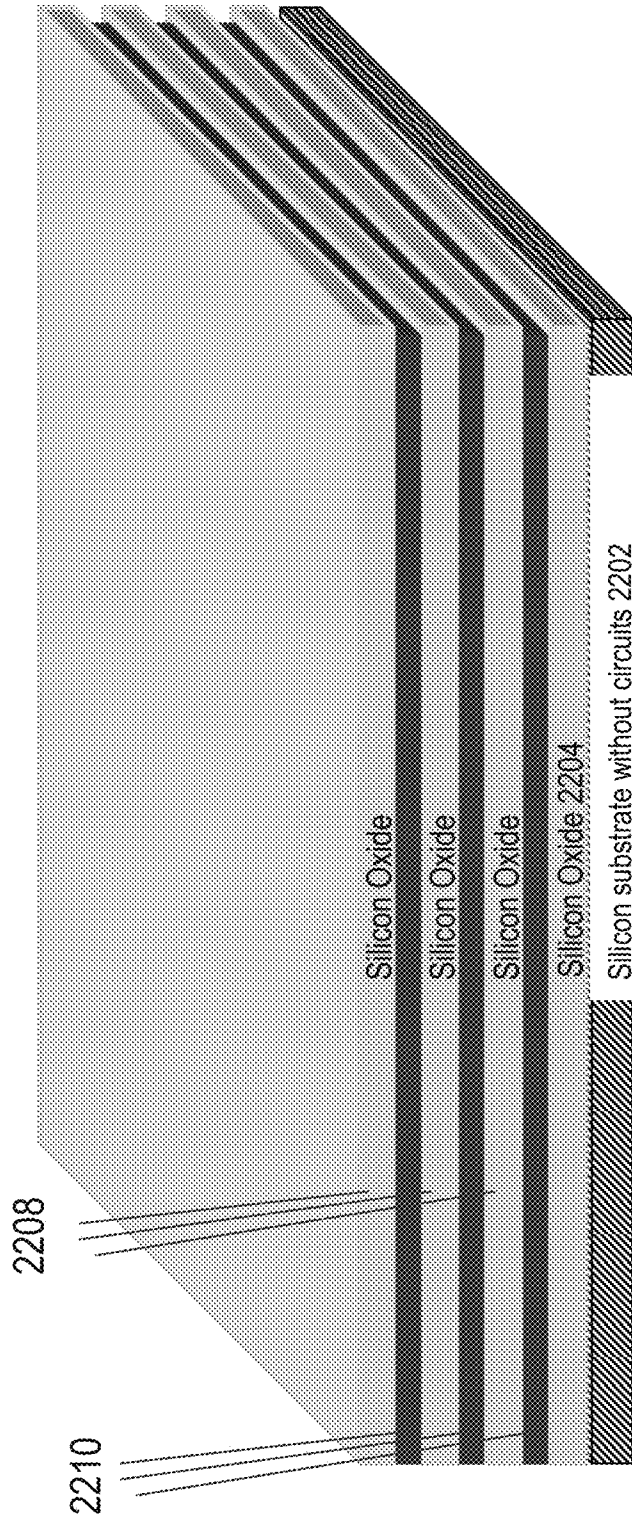


Fig. 22C

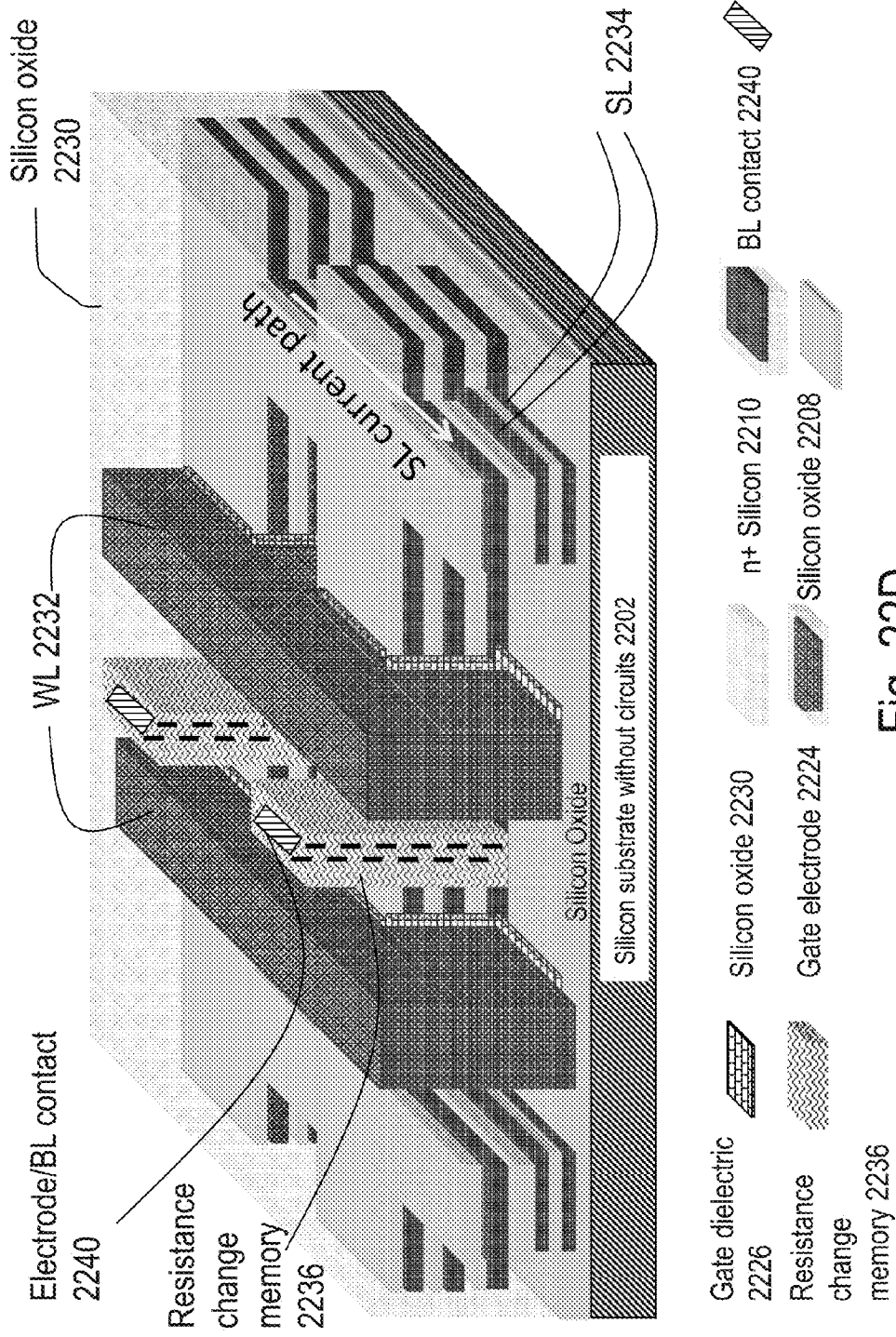


Fig. 22D

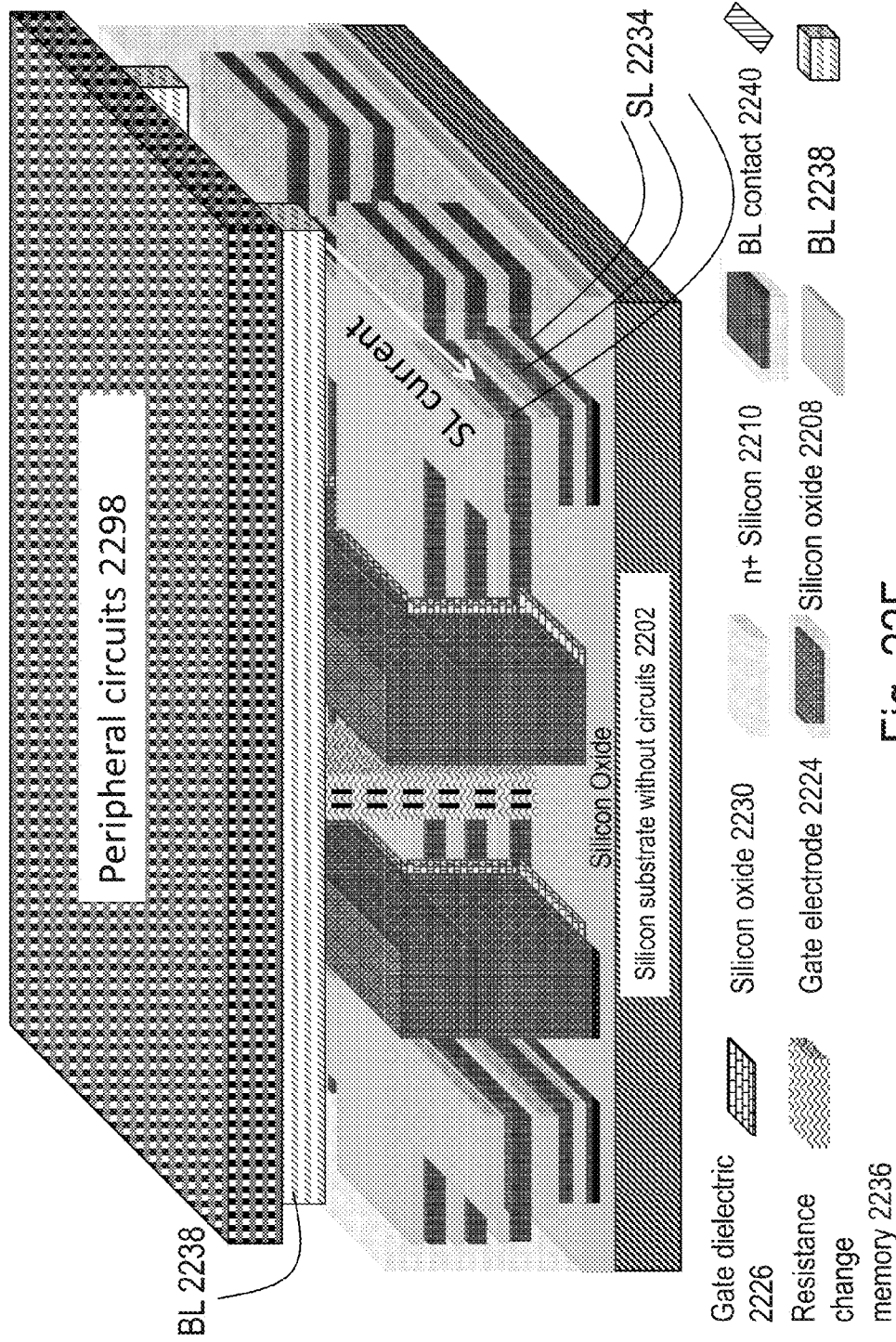


Fig. 22F

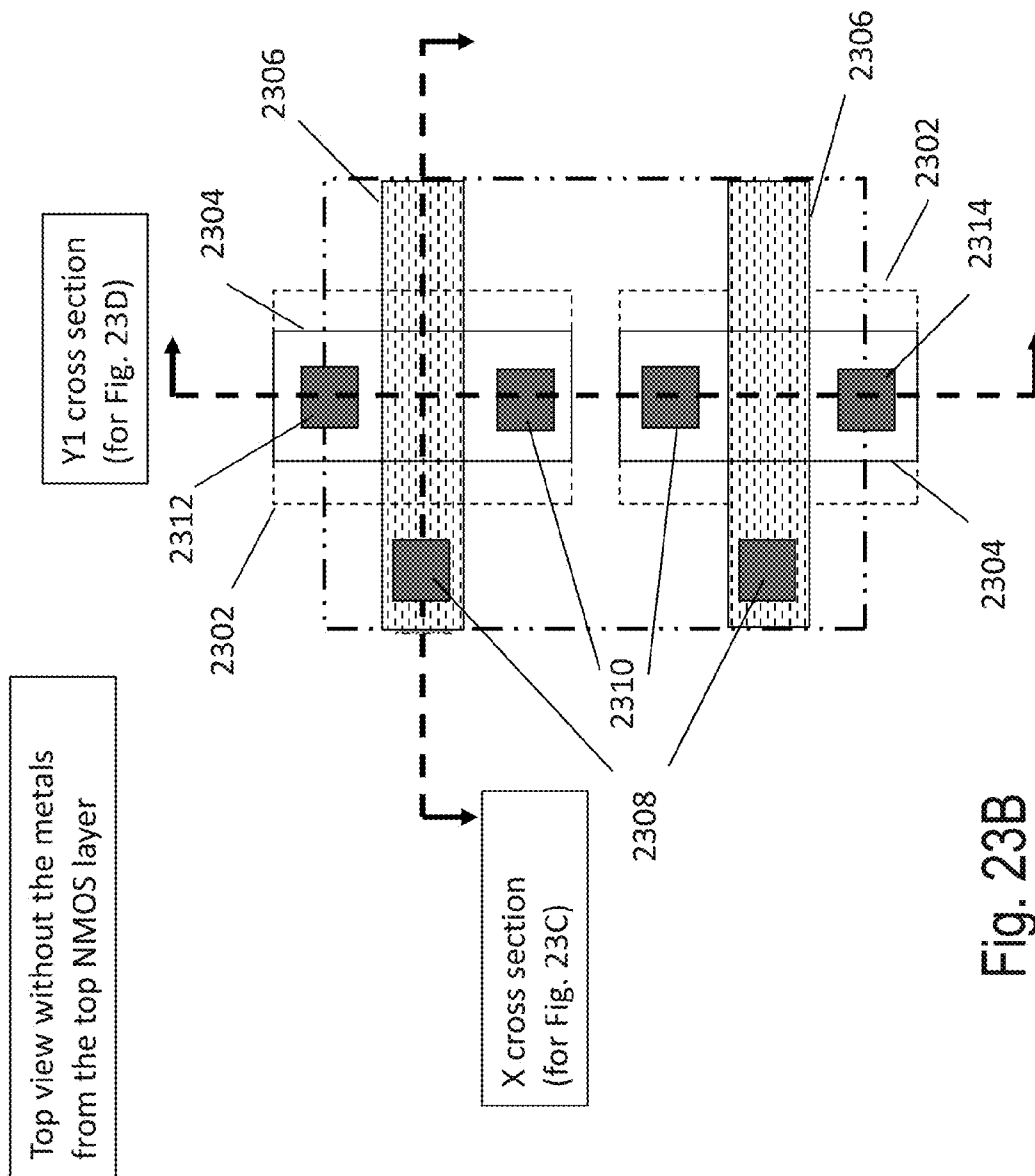


Fig. 23B

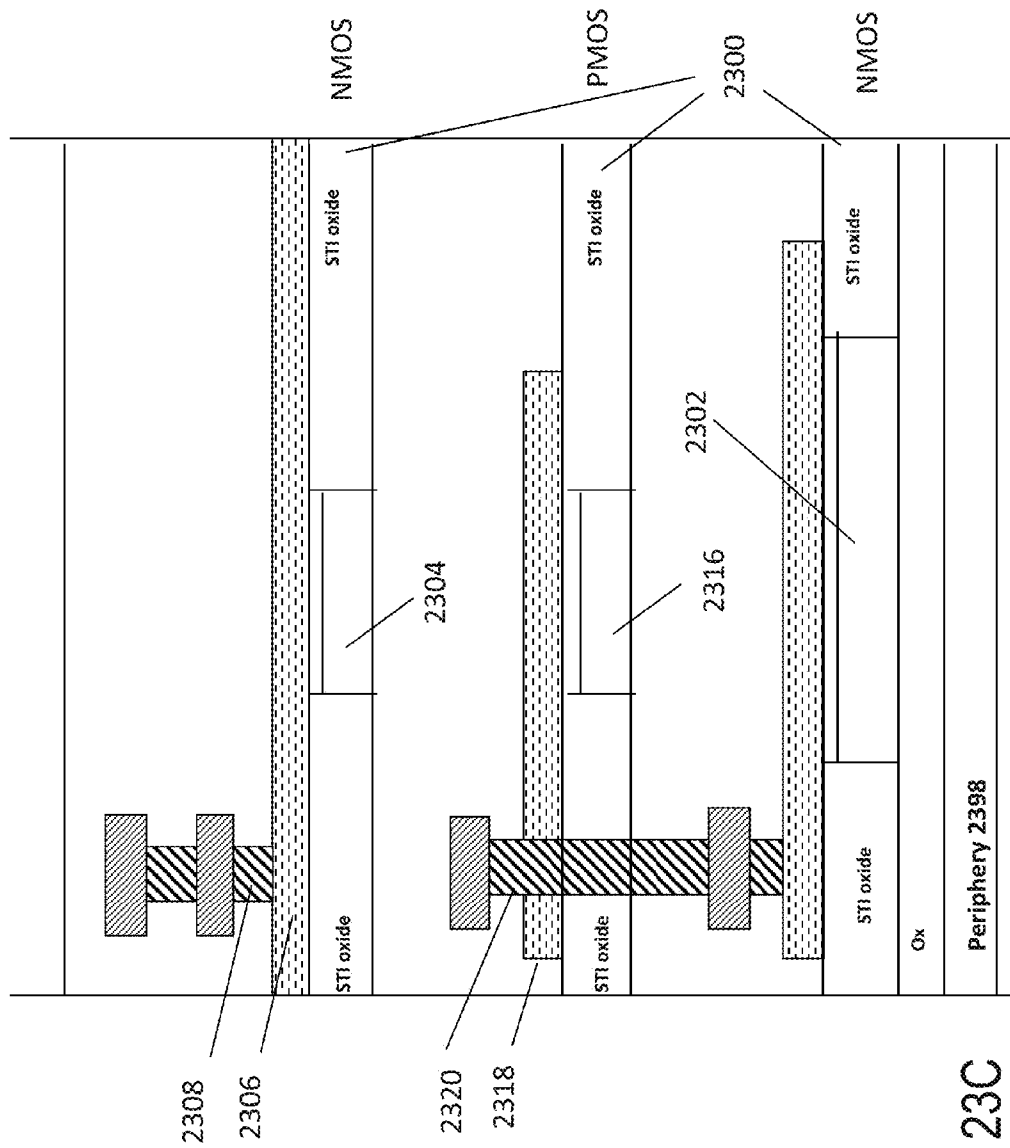


Fig. 23C

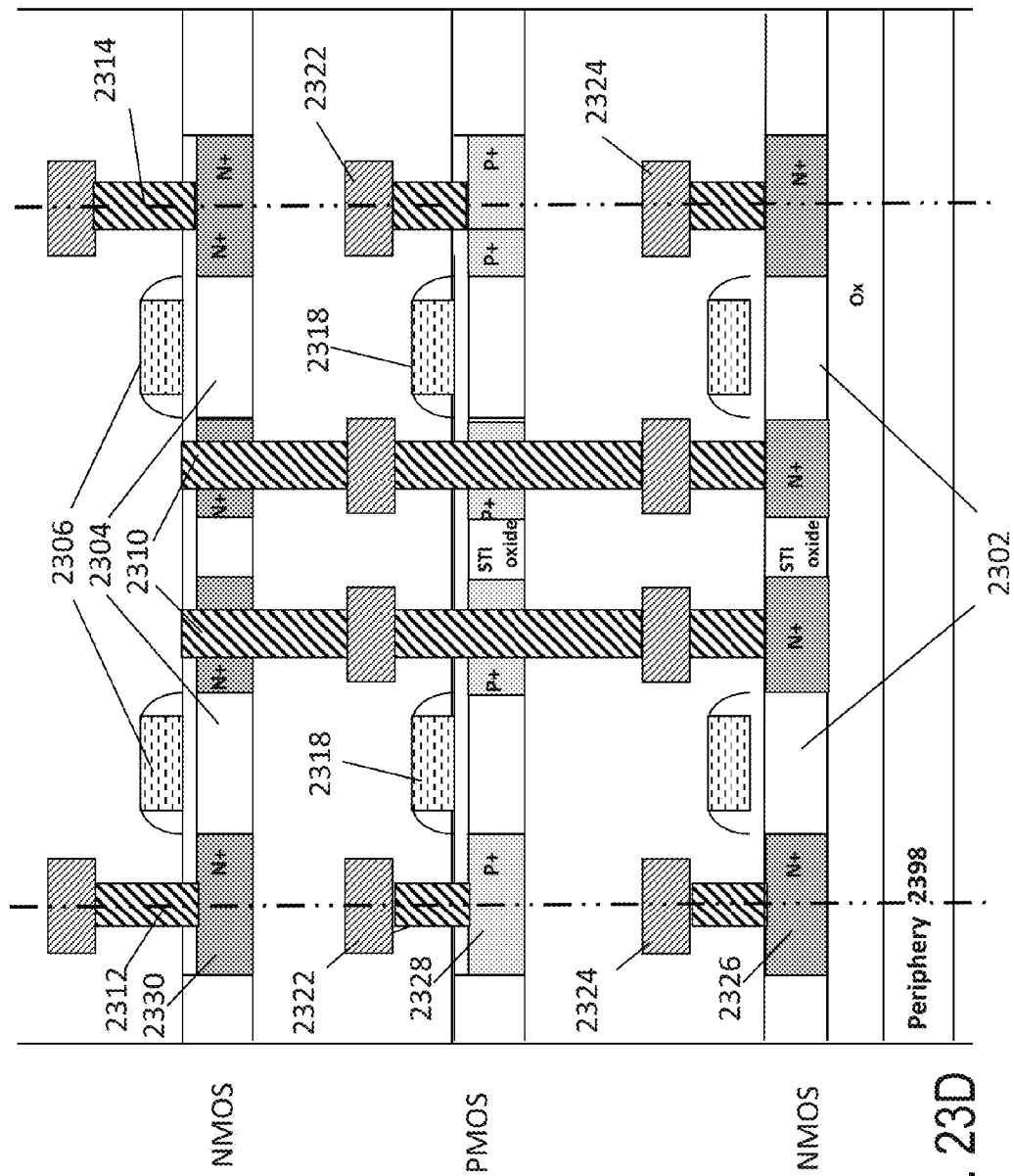


Fig. 23D

3DIC SYSTEM WITH A TWO STABLE STATE MEMORY AND BACK-BIAS REGION

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 13/792,202, which was filed on Mar. 11, 2013, now U.S. Pat. No. 8,902,663; the entire contents of the foregoing are incorporated by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to the field of monolithic 3D integration to semiconductor chips performing logic and/or memory functions.

2. Discussion of Background Art

Over the past 40 years, the microelectronic industry has seen a dramatic increase in functionality and performance of Integrated Circuits (ICs). This has largely been due to the phenomenon of “scaling” i.e. component sizes within ICs have been reduced (“scaled”) with every successive generation of technology. There are two main classes of components in Complimentary Metal Oxide Semiconductor (CMOS) ICs, namely transistors and wires. With “scaling”, transistor performance and density typically improve and this has contributed to the previously-mentioned increases in IC performance and functionality. However, wires (interconnects) that connect together transistors degrade in performance with “scaling”. The situation today is that wires dominate performance, functionality and power consumption of ICs.

3D stacking of semiconductor chips is one avenue to tackle issues with wires. By arranging transistors in 3 dimensions instead of 2 dimensions (as was the case in the 1990s), one can place transistors in ICs closer to each other. This reduces wire lengths and keeps wiring delay low. However, there are many barriers to practical implementation of 3D stacked chips. These include:

Constructing transistors in ICs typically require high temperatures (higher than $\sim 700^\circ\text{C}$.) while wiring levels are constructed at low temperatures (lower than $\sim 400^\circ\text{C}$.) Copper or Aluminum wiring levels, in fact, can get damaged when exposed to temperatures higher than $\sim 400^\circ\text{C}$. If one would like to arrange transistors in 3 dimensions along with wires, it has the challenge described below. For example, let us consider a 2 layer stack of transistors and wires i.e. Bottom Transistor Layer, above it Bottom Wiring Layer, above it Top Transistor Layer and above it Top Wiring Layer. When the Top Transistor Layer is constructed using Temperatures higher than 700°C ., it can damage the Bottom Wiring Layer.

Due to the above mentioned problem with forming transistor layers above wiring layers at temperatures lower than 400°C ., the semiconductor industry has largely explored alternative architectures for 3D stacking. In these alternative architectures, Bottom Transistor Layers, Bottom Wiring Layers and Contacts to the Top Layer are constructed on one silicon wafer. Top Transistor Layers, Top Wiring Layers and Contacts to the Bottom Layer are constructed on another silicon wafer. These two wafers are bonded to each other and contacts are aligned, bonded and connected to each other as well. Unfortunately, the size of Contacts to the other Layer is large and the number of these Contacts is

small. In fact, prototypes of 3D stacked chips today utilize as few as 10,000 connections between two layers, compared to billions of connections within a layer. This low connectivity between layers is because of two reasons: (i) Landing pad size needs to be relatively large due to alignment issues during wafer bonding. These could be due to many reasons, including bowing of wafers to be bonded to each other, thermal expansion differences between the two wafers, and lithographic or placement misalignment. This misalignment between two wafers limits the minimum contact landing pad area for electrical connection between two layers; (ii) The contact size needs to be relatively large. Forming contacts to another stacked wafer typically involves having a Through-Silicon Via (TSV) on a chip. Etching deep holes in silicon with small lateral dimensions and filling them with metal to form TSVs is not easy. This places a restriction on lateral dimensions of TSVs, which in turn impacts TSV density and contact density to another stacked layer. Therefore, connectivity between two wafers is limited.

It is highly desirable to circumvent these issues and build 3D stacked semiconductor chips with a high-density of connections between layers. To achieve this goal, it is sufficient that one of three requirements must be met: (1) A technology to construct high-performance transistors with processing temperatures below $\sim 400^\circ\text{C}$.; (2) A technology where standard transistors are fabricated in a pattern, which allows for high density connectivity despite the misalignment between the two bonded wafers; and (3) A chip architecture where process temperature increase beyond 400°C . for the transistors in the top layer does not degrade the characteristics or reliability of the bottom transistors and wiring appreciably. This patent application describes approaches to address options (1), (2) and (3) in the detailed description section. In the rest of this section, some background art that has previously tried to address options (1), (2) and (3) will be described.

U.S. Pat. No. 7,052,941 from Sang-Yun Lee (“S-Y Lee”) describes methods to construct vertical transistors above wiring layers at less than 400°C . In these single crystal Si transistors, current flow in the transistor’s channel region is in the vertical direction. Unfortunately, however, almost all semiconductor devices in the market today (logic, DRAM, flash memory) utilize horizontal (or planar) transistors due to their many advantages, and it is difficult to convince the industry to move to vertical transistor technology.

A paper from IBM at the Intl. Electron Devices Meeting in 2005 describes a method to construct transistors for the top stacked layer of a 2 chip 3D stack on a separate wafer. This paper is “Enabling SOI-Based Assembly Technology for Three-Dimensional (3D) Integrated Circuits (ICs),” *IEDM Tech. Digest*, p. 363 (2005) by A. W. Topol, D. C. La Tulipe, L. Shi, et al. (“Topol”). A process flow is utilized to transfer this top transistor layer atop the bottom wiring and transistor layers at temperatures less than 400°C . Unfortunately, since transistors are fully formed prior to bonding, this scheme suffers from misalignment issues. While Topol describes techniques to reduce misalignment errors in the above paper, the techniques of Topol still suffer from misalignment errors that limit vertical contact dimensions between two chips in the stack to $>130\text{ nm}$, and; hence, limits device density.

The textbook “Integrated Interconnect Technologies for 3D Nanoelectronic Systems” by Bakir and Meindl (“Bakir”) describes a 3D stacked DRAM concept with horizontal (i.e. planar) transistors. Silicon for stacked transistors is pro-

duced using selective epitaxy technology or laser recrystallization. Unfortunately, however, these technologies have higher defect density compared to standard single crystal silicon and do not provide a mono-crystalline stacked layer or layers. This higher defect density degrades transistor performance and device yield.

In the NAND flash memory industry, several organizations have attempted to construct 3D stacked memory. These attempts predominantly use transistors constructed with poly-Si or selective epi technology as well as charge-trap concepts. References that describe these attempts to 3D stacked memory include "Integrated Interconnect Technologies for 3D Nanoelectronic Systems", Artech House, 2009 by Bakir and Meindl ("Bakir"), "Bit Cost Scalable Technology with Punch and Plug Process for Ultra High Density Flash Memory", Symp. VLSI Technology Tech. Dig. pp. 14-15, 2007 by H. Tanaka, M. Kido, K. Yahashi, et al. ("Tanaka"), "A Highly Scalable 8-Layer 3D Vertical-Gate (VG) TFT NAND Flash Using Junction-Free Buried Channel BE-SONOS Device," Symposium on VLSI Technology, 2010 by W. Kim, S. Choi, et al. ("W. Kim"), "A Highly Scalable 8-Layer 3D Vertical-Gate (VG) TFT NAND Flash Using Junction-Free Buried Channel BE-SONOS Device," Symposium on VLSI Technology, 2010 by Hang-Ting Lue, et al. ("Lue") and "Sub-50 nm Dual-Gate Thin-Film Transistors for Monolithic 3-D Flash", IEEE Trans. Elect. Dev., vol. 56, pp. 2703-2710, November 2009 by A. J. Walker ("Walker"). An architecture and technology that utilizes single crystal Silicon using epi growth is described in "A Stacked SONOS Technology, Up to 4 Levels and 6 nm Crystalline Nanowires, with Gate-All-Around or Independent Gates (Φ Flash), Suitable for Full 3D Integration", International Electron Devices Meeting, 2009 by A. Hubert, et al ("Hubert"). However, the approach described by Hubert has some challenges including the use of difficult-to-manufacture nanowire transistors, higher defect densities due to formation of Si and SiGe layers atop each other, high temperature processing for long times, difficult manufacturing, etc.

It is clear based on the background art mentioned above that invention of novel technologies for 3D stacked chips will be useful.

SUMMARY

In one aspect, a 3D IC based system, comprising: a first layer comprising first transistors; a second layer overlying said first layer, said second layer comprises a plurality of second transistors, wherein said second layer comprises at least one through second layer via having a diameter of less than 400 nm, and wherein at least one of said plurality of second transistors forms a two stable state memory cell comprising a back-bias region.

In another aspect, a 3D IC based system, comprising: a first layer comprising first transistors; a second layer overlying said first layer, said second layer comprises a plurality of second transistors, wherein said second layer thickness is less than 400 nm, and wherein at least one of said plurality of second transistors forms a two stable state memory cell comprising a back-bias region.

In another aspect, a 3D IC based system, comprising: a first layer comprising first transistors; a second layer overlying said first layer, said second layer comprises a plurality of second transistors, wherein a first portion of at least one of said first transistors is self-aligned to a second portion of at least one of said plurality of second transistors, and

wherein at least one of said plurality of second transistors forms a two stable state memory cell comprising a back-bias region.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a drawing illustration of a floating-body DRAM;

FIG. 2A-2M are drawing illustrations of a one-mask per layer 3D floating body DRAM;

FIG. 3A-3K are drawing illustrations of a zero-mask per layer 3D floating body DRAM;

FIG. 4A-4G are drawing illustrations of techniques to refresh floating body DRAM cells;

FIG. 5A-5H are drawing illustrations of additional techniques to refresh floating body DRAM cells;

FIG. 6 is a drawing illustration of a floating body memory cell;

FIG. 7A-7J are drawing illustrations of a 3D floating body DRAM with two stable states;

FIG. 7K-7L are drawing illustrations of a 3D floating body DRAM dual port RAM with two stable states;

FIG. 7M-7N are drawing illustrations of a 3D floating body DRAM dual port RAM with integrated select transistors with two stable states;

FIG. 8 is a drawing illustration of an architecture with a shared bit line access device;

FIG. 9 is a drawing illustration of two stable states memory back bias region formed in the same mono-crystalline layer/region as the floating body channel;

FIG. 10A-10J are drawing illustrations of a zero-mask per layer 3D resistive memory with a junction-less transistor;

FIG. 11A-11K are drawing illustrations of an alternative zero-mask per layer 3D resistive memory;

FIG. 12A-12L are drawing illustrations of a one-mask per layer 3D resistive memory;

FIG. 13A-13F are drawing illustrations of a two-mask per layer 3D resistive memory;

FIG. 14A-14F are drawing illustrations of a two-mask per layer 3D charge-trap memory;

FIG. 15A-15G are drawing illustrations of a zero-mask per layer 3D charge-trap memory;

FIG. 16A-16D are drawing illustrations of a fewer-masks per layer 3D horizontally-oriented charge-trap memory;

FIG. 17A-17F are drawing illustrations of a two-mask per layer 3D horizontally-oriented floating-gate memory;

FIG. 18A-18H are drawing illustrations of a one-mask per layer 3D horizontally-oriented floating-gate memory;

FIG. 19A-19B are drawing illustrations of periphery on top of memory layers;

FIG. 20A-20E are drawing illustrations of a method to make high-aspect ratio vias in 3D memory architectures;

FIG. 21A-21E are drawing illustrations of polysilicon select devices for 3D memory and peripheral circuits at the bottom according to some embodiments of the current invention;

FIG. 22A-22F are drawing illustrations of polysilicon select devices for 3D memory and peripheral circuits at the top according to some embodiments of the current invention; and

FIG. 23A-23D are drawing illustrations of a monolithic 3D SRAM according to some embodiments of the current invention.

DETAILED DESCRIPTION

Embodiments of the invention are now described with reference to the indicated figures, it being appreciated that

the figures illustrate the subject matter not to scale or to measure. Many figures describe process flows for building devices. These process flows, which may be a sequence of steps for building a device, may have many structures, numerals and labels that may be common between two or more adjacent steps. In such cases, some labels, numerals and structures used for a certain step's figure may have been described in previous steps' figures.

The entirety of U.S. Pat. No. 8,379,458, U.S. Pat. No. 8,273,610 and U.S. Pat. No. 8,803,206 are incorporated herein by reference.

Section 1: Monolithic 3D DRAM.

This Section describes some novel monolithic 3D Dynamic Random Access Memories (DRAMs). Some embodiments of this invention may involve floating body DRAM. Background information on floating body DRAM and its operation is given in "Floating Body RAM Technology and its Scalability to 32 nm Node and Beyond," *Electron Devices Meeting, 2006. IEDM '06. International*, vol., no., pp. 1-4, 11-13 Dec. 2006 by T. Shino, N. Kusunoki, T. Higashi, et al., Overview and future challenges of floating body RAM (FBRAM) technology for 32 nm technology node and beyond, *Solid-State Electronics, Volume 53, Issue 7, Papers Selected from the 38th European Solid-State Device Research Conference—ESSDERC'08, July 2009*, Pages 676-683, ISSN 0038-1101, DOI: 10.1016/j.sse.2009.03.010 by Takeshi Hamamoto, Takashi Ohsawa, et al., "New Generation of Z-RAM," *Electron Devices Meeting, 2007. IEDM 2007. IEEE International*, vol., no., pp. 925-928, 10-12 Dec. 2007 by Okhonin, S.; Nagoga, M.; Carman, E., et al. The above publications are incorporated herein by reference.

As illustrated in FIG. 1 the fundamentals of operating a floating body DRAM are described. In order to store a '1' bit, excess holes 102 may exist in the floating body region 120 and change the threshold voltage of the memory cell transistor including source 104, gate 106, drain 108, floating body region 120, and buried oxide (BOX) 118. This is shown in FIG. 1(a). The '0' bit may correspond to no charge being stored in the floating body region 120 and may affect the threshold voltage of the memory cell transistor including source 110, gate 112, drain 114, floating body region 120, and buried oxide (BOX) 116. This is shown in FIG. 1(b). The difference in threshold voltage between the memory cell transistor depicted in FIG. 1(a) and FIG. 1(b) may manifest itself as a change in the drain current 134 of the transistor at a particular gate voltage 136. This is described in FIG. 1(c). This current differential 130 may be sensed by a sense amplifier circuit to differentiate between '0' and '1' states and thus function as a memory bit.

FIGS. 2A-M describe a flow to construct a horizontally-oriented monolithic 3D DRAM (Dynamic Random Access Memory). This monolithic 3D DRAM utilizes the floating body effect and double-gate transistors. One mask is utilized on a "per-memory-layer" basis for the monolithic 3D DRAM concept shown in FIG. 2A-M, while other masks are shared between different layers. The process flow may include several steps that occur in the following sequence.

Step (A): Peripheral circuits with tungsten, or conventional aluminum/copper, wiring 202 are first constructed and above this a layer of silicon dioxide 204 is deposited. FIG. 2A illustrates the structure after Step (A). This presented process flow suggests the use of tungsten wiring or other refractory metal so the following process steps could include high temperature steps. These high temperature steps may include higher than 400° C. such as 800° C. or even 900° C. for dopant activation or damage annealing steps. Optical

annealing and shielding may also be utilized, as described in the referenced patents. So the peripheral circuits activation could be delayed to those later high temperature steps.

Step (B): FIG. 2B shows a drawing illustration after Step (B). A wafer of p-Silicon 206 has an oxide layer 208 grown or deposited above it. Following this, hydrogen is implanted into the p-Silicon wafer at a certain depth indicated by 210. Alternatively, some other atomic species such as Helium could be (co-)implanted. A portion of this hydrogen implanted p-Silicon wafer 206 may form the top layer 212. The bottom layer 214 may include the peripheral circuits 202 with oxide layer 204. The top layer 212 may be flipped and bonded to the bottom layer 214 using oxide-to-oxide bonding. Step (C): FIG. 2C illustrates the structure after Step (C). The stack of top and bottom wafers after Step (B) may be cleaved at the hydrogen plane 210 using either an anneal or a sideways mechanical force or other means. A CMP (Chemical Mechanical Polishing) process may then be conducted. At the end of this step, a single-crystal transferred p-layer 207 exists atop the peripheral circuits, and this has been achieved using layer-transfer techniques. A defect anneal step at about 800° C. could be applied to repair defects caused to the layer transferred p-layer 207 from the ion implant step used for the layer transfer. The thickness of transferred p-layer 207 could be set to be very thin, such as, for example, 5 nm or less and could be few tens of nm such as 50 nm or 100 nm or even thicker. In many case the preference could be for thin or very thin to reduce the aspect ratio of the following deep etch steps. These will be true for the many architectures and flow/structure variations presented hereinafter.

Step (D): FIG. 2D illustrates the structure after Step (D). Using lithography and then ion implantation, n+ regions 216 and p- regions 218 may be formed on the transferred p-layer 207 after Step (C). This lithography step and all the following lithography steps may be aligned to the underlying peripheral circuits 202. Alignment marks included in those layer or layers could be used as the overlying layers oxide layer 204, oxide layer 208 and transferred p-layer 207 are thin enough to so the stepper could align to the alignment marks included in the peripheral circuits layers 202. The alignment accuracy could be better than 10 nm and far less than 40 nm. The oxide layer 204 and oxide layer 208 thicknesses could be less than 100 nm and the transferred p-silicon layer 207 could be less than 100 nm as well.

Step (E): FIG. 2E illustrates the structure after Step (E). An oxide layer 220 may be deposited atop the structure obtained after Step (D). A first layer of Si/SiO₂ 222 is therefore formed atop the peripheral circuit layer 202. The composition of the 'SiO₂' layer within the stacked Si/SiO₂ layers such as Si/SiO₂ 222, may be insulators or dielectrics other than silicon dioxide such as, for example, a low-k dielectric, carbon containing silicon oxides, amorphous carbon. The thickness of the 'SiO₂' insulator layer within the stacked Si/SiO₂ layers such as Si/SiO₂ 222 may be adjusted to minimize layer to layer, strata to strata disturb mechanisms, and may include thicknesses of 50 nm, 75 nm, 100 nm, 150 nm, 200 nm, 500 nm, and less than 1000 nm. A thin conductive layer, such as a metal, may also be formed between the two bonding oxides to form a field shield to mitigate layer to layer, strata to strata disturb mechanisms, and may be electrically floating or tied to a bias, such as ground or Vdd.

Step (F): FIG. 2F illustrates the structure after Step (F). Using procedures similar to Steps (B)-(E), additional Si/SiO₂ layers 224 and 226 are formed atop Si/SiO₂ layer 222. A rapid thermal anneal (RTA) or spike anneal or flash

anneal or laser anneal may then be done to activate all implanted layers **222**, **224** and **226** (and possibly also the peripheral circuit layer **202**). Alternatively, the layers **222**, **224** and **226** may be annealed layer-by-layer as soon as their implantations are done using a laser anneal system. The stacked Si/SiO₂ layers, such as Si/SiO₂ **222**, may alternatively be formed by successive ion implants of oxygen atoms/ions to various depths from the top surface of a mono-crystalline silicon wafer/substrate and then heat treated to form oxide layers thus forming silicon layers in-between the oxide layers, a layered 'SIMOX' process approach.

Step (G): FIG. 2G illustrates the structure after Step (G). Lithography and etch processes may then be utilized to make a structure such as, for example, as shown in the FIG. 2G. The structure may include p- regions **219** and N+ regions **217**, any may be separated in the vertical direction from other conductive regions by a silicon oxide.

Step (H): FIG. 2H illustrates the structure after Step (H). Gate dielectric **228** and gate electrode **230** may then be deposited following which a CMP may be done to planarize the gate electrode **230** regions. Lithography and etch may be utilized to define gate regions over the p-silicon regions (eg. p-Si region after Step (D)). Note that gate width could be slightly larger than p- region width to compensate for overlay errors in lithography. Gate dielectric **228** and gate electrode **230** may be, for example, a HKMG structure or a TEL SPA radical oxidation oxide and an appropriate work function electrode, for example, tungsten, degenerately doped polysilicon or amorphous silicon. Although the width of the N+ regions **217** near and under the gates are illustrated as being larger than the thickness, one skilled in the art would recognize that the reverse (i.e., thickness larger than width) could be formed to provide increased gate control of the transistor channel.

Step (I): FIG. 2I illustrates the structure after Step (I). A silicon oxide layer **232** may then be deposited and planarized. For clarity, the silicon oxide layer is shown transparent in the figure, along with word-line (WL) and source-line (SL) regions.

Step (J): FIG. 2J illustrates the structure after Step (J). Bit-line (BL) contacts **234** are formed by etching and deposition. These BL contacts may be shared among all layers of the memory. Bit line contacts may be formed, for example, as sidewall structures or end-wall structures, with various overlaps as required by the process and layout.

Step (K): FIG. 2K illustrates the structure after Step (K). Bit Lines such as BL **236** may then be constructed. Contacts can be made to BLs, WLs and SLs of the memory array at its edges. SL contacts can be made into stair-like structures using techniques described in "Bit Cost Scalable Technology with Punch and Plug Process for Ultra High Density Flash Memory," *VLSI Technology, 2007 IEEE Symposium on*, vol., no., pp. 14-15, 12-14 Jun. 2007 by Tanaka, H.; Kido, M.; Yahashi, K.; Oomura, M.; et al., following which contacts can be constructed to them. Formation of stair-like structures for SLs could be done in steps prior to Step (K) as well.

FIG. 2L shows cross-sectional views of the array for clarity. The double-gated transistors in FIG. 2L can be utilized along with the floating body effect for storing information. FIG. 2M shows an illustration of a memory cell of the floating body RAM array with two gates, such as gate electrode **230** and gate dielectric **228**, on either side of the p- region **219**. Insulator region SiO₂ **238** may provide strata to strata isolation.

A floating-body DRAM has thus been constructed, with (1) horizontally-oriented transistors—i.e., current flowing in

substantially the horizontal direction in transistor channels, (2) some of the memory cell control lines, e.g., source-lines SL, constructed of heavily doped silicon and embedded in the memory cell layer, (3) side gates simultaneously deposited over multiple memory layers, and (4) monocrystalline (or single-crystal) silicon layers obtained by layer transfer techniques such as ion-cut.

FIGS. 3A-K describe another process flow to construct a horizontally-oriented monolithic 3D DRAM. This monolithic 3D DRAM utilizes the floating body effect and double-gate transistors. No mask is utilized on a "per-memory-layer" basis for the monolithic 3D DRAM concept shown in FIGS. 3A-K, and all other masks are shared between different layers. The process flow may include several steps in the following sequence.

Step (A): Peripheral circuits with tungsten, or conventional aluminum/copper, wiring **302** are first constructed and above this a layer of silicon dioxide **304** may be deposited. FIG. 3A shows a drawing illustration after Step (A).

Step (B): FIG. 3B illustrates the structure after Step (B). A wafer of p-Silicon **308** has an oxide layer **306** grown or deposited above it. Following this, hydrogen may be implanted into the p-Silicon wafer at a certain depth indicated by **314**. Alternatively, some other atomic species such as Helium could be (co-)implanted. This hydrogen implanted p-Silicon wafer **308** may form top layer **310**. The bottom layer **312** may include the peripheral circuits **302** with oxide layer **304**. The top layer **310** may be flipped and bonded to the bottom layer **312** using oxide-to-oxide bonding.

Step (C): FIG. 3C illustrates the structure after Step (C). The bonded stack of top and bottom wafers after Step (B) may be cleaved at the hydrogen plane **314** using either a anneal or a sideways mechanical force or other means. A CMP process may then be conducted. A layer of silicon oxide **318** may be deposited atop the p-Silicon layer **316**. Thus, a single-crystal p-Si layer **316** may be atop the peripheral circuits, and this has been achieved using layer-transfer techniques.

Step (D): FIG. 3D illustrates the structure after Step (D). Using methods similar to Step (B) and (C), multiple p-silicon layers **320** may be formed with silicon oxide layers in between. The composition of the 'SiO₂' layer within the stacked p-Si/SiO₂ layers may be insulators or dielectrics other than silicon dioxide such as, for example, a low-k dielectric, carbon containing silicon oxides, amorphous carbon. The thickness of the 'SiO₂' insulator layer within the stacked p-Si/SiO₂ layers may be adjusted to minimize layer to layer, strata to strata disturb mechanisms, and may include thicknesses of 50 nm, 75 nm, 100 nm, 150 nm, 200 nm, 500 nm, and less than 1000 nm. A thin conductive layer, such as a metal, may also be formed between the two bonding oxides to form a field shield to mitigate layer to layer, strata to strata disturb mechanisms, and may be electrically floating or tied to a bias, such as ground or Vdd. The stacked Si/SiO₂ layers, may alternatively be formed by successive ion implants of oxygen atoms/ions to various depths from the top surface of a mono-crystalline silicon wafer/substrate and then heat treated to form oxide layers thus forming silicon layers in-between the oxide layers, a layered SIMOX' process approach.

Step (E): FIG. 3E illustrates the structure after Step (E) including silicon oxide regions **322**. Lithography and etch processes may be utilized to make a structure, such as, for example, as shown in FIG. 3E.

Step (F): FIG. 3F illustrates the structure after Step (F). Gate dielectric **326** and gate electrode **324** may be deposited

following which a CMP may be done to planarize the gate electrode **324** regions. Lithography and etch are utilized to define gate regions. Gate dielectric **326** and gate electrode **324** may be, for example, a HKMG structure or a TEL SPA radical oxidation oxide and an appropriate work function electrode, for example, tungsten, degenerately doped polysilicon or amorphous silicon. Although the width of the p-regions **321** near and under the gates are illustrated as being larger than the thickness, one skilled in the art would recognize that the reverse (i.e., thickness larger than width) could be formed to provide increased gate control of the transistor channel.

Step (G): FIG. 3G illustrates the structure after Step (G) including N+ silicon regions **328**. Using the hard mask (and remaining photoresist may be utilized as part of the 'hard mask') defined in Step (F), p- regions not covered by the gate may be implanted to form n+ regions. Spacers may be utilized during this multi-step implantation process and layers of silicon present in different layers of the stack may have different spacer widths to account for lateral straggle of buried layer implants. Bottom layers could have larger spacer widths than top layers. A thermal annealing step, such as an RTA or spike anneal or laser anneal or flash anneal, may be conducted to activate the n+ implanted doped regions. The optical anneal system, such as the laser, spike, flash anneals, may be utilized to crystallize the polysilicon or amorphous silicon.

Step (H): FIG. 3H illustrates the structure after Step (H). A silicon oxide layer **330** may be deposited and planarized. For clarity, the silicon oxide layer is shown transparent, along with word-line (WL) **332** and source-line (SL) **334** regions.

Step (I): FIG. 3I illustrates the structure after Step (I). Bit-line (BL) contacts **336** are formed by etching and deposition. These BL contacts may be shared among the layers of memory. Bit line contacts may be formed, for example, as sidewall structures or end-wall structures, with various overlaps as required by the process and layout.

Step (J): FIG. 3J illustrates the structure after Step (J). BLs **338** may be constructed. Contacts may be made to BLs, WLs and SLs of the memory array at its edges. SL contacts can be made into stair-like structures using techniques described in "Bit Cost Scalable Technology with Punch and Plug Process for Ultra High Density Flash Memory," *VLSI Technology*, 2007 *IEEE Symposium on*, vol., no., pp. 14-15, 12-14 Jun. 2007 by Tanaka, H.; Kido, M.; Yahashi, K.; Oomura, M.; et al., following which contacts can be constructed to them. Formation of stair-like structures for SLs could be done in steps prior to Step (J) as well.

FIG. 3K shows cross-sectional views of the array for clarity. Double-gated transistors may be utilized along with the floating body effect for storing information.

A floating-body DRAM has thus been constructed, with (1) horizontally-oriented transistors—i.e. current flowing in substantially the horizontal direction in transistor channels (2) some of the memory cell control lines, e.g., source-lines SL, constructed of heavily doped silicon and embedded in the memory cell layer, (3) side gates simultaneously deposited over multiple memory layers, and (4) monocrystalline (or single-crystal) silicon layers obtained by layer transfer techniques such as ion-cut.

With the explanations for the formation of monolithic 3D DRAM with ion-cut in this section, it is clear to one skilled in the art that alternative implementations are possible. BL and SL nomenclature has been used for two terminals of the 3D DRAM array, and this nomenclature can be interchanged. Each gate of the double gate 3D DRAM can be independently controlled for better control of the memory

cell. To implement these changes, the process steps in FIGS. 2 and 3 may be modified. Moreover, selective epi technology or laser recrystallization technology could be utilized for implementing structures shown in FIG. 2A-M and FIG. 3A-K. Various other types of layer transfer schemes and anneal/shielding techniques that have been described in the referenced and incorporated patents can be utilized for construction of various 3D DRAM structures. Furthermore, buried wiring, i.e. where wiring for memory arrays is below the memory layers but above the periphery, may also be used. In addition, other variations of the monolithic 3D DRAM concepts are possible, such as, for example, forming the periphery circuits above and/or below the memory stack layers.

The positive charge stored, such as in the floating body DRAM described in FIGS. 2-3, may decrease over time due to the diode leakage current of the p-n junctions formed between the floating body and n+ regions and due to charge recombination. A method to refresh all memory cells in parallel have been described in "Autonomous Refresh of Floating Body Cell (FBC)", Ohsawa et al., pp. 801-804, International Electron Device Meeting, 2008 ("Ohsawa"), U.S. Pat. No. 7,170,807 "Data Storage Device and Refreshing Method for Use with Such Device", Fazan et al. ("Fazan") and in U.S. Pat. No. 8,264,875 "A Semiconductor Memory Device Having an Electrically Floating Body Transistor", Widjaja and Or-Bach ("Widjaja"), which are incorporated by reference herein in entirety. Ohsawa and Fazan teach an autonomous refresh method by applying a periodic gate and drain voltage pulses and Widjaja describes a parallel refresh method by applying a bias to the back bias terminal.

FIG. 4A is a drawing illustration of the cross-section of a memory cell **450** in a memory layer of the 3D DRAM device shown in FIG. 2L. FIG. 4B is a drawing illustration of the equivalent circuit representation of the memory cell shown in FIG. 4A. The refresh operation will be described with reference to FIGS. 4A and 4B, although the same principle applies to other 3D DRAM described herein, for example, as shown in FIG. 3K.

As shown in FIG. 4A, memory cell **450** may include a floating body **424** of p-type conductivity. The floating body **424** may be bounded by an insulating region **422**, n+ regions **416** and **418**, and by the surface **414**. A gate **460** may be positioned in-between the n+ regions **416** and **418**, and may be insulated from the floating body region **424** by an insulating layer **462**, and may be connected to gate connectivity **470**.

As shown in FIG. 4B, inherent in the each of the floating body DRAM memory cells **450** is n-p-n bipolar device **430** formed by n+ region **416** (the collector region), floating body **424** (the base region), and n+ region **418** (the emitter region). The collector n+ region **416** can be connected to the SL terminal **472** and the emitter region **418** can be connected to the BL terminal **474**, or vice versa. The refresh operation can be performed by applying a positive voltage to the collector n+ region **416** while simultaneously grounding the emitter region **418**. The refresh operation is relatively independent of the voltage applied to gate **460**. In some embodiments of the invention, the gate may be grounded.

If floating body **424** is sufficiently positively charged, a state corresponding to logic-1, the bipolar device **430** will be turned on. In particular, the voltage across the reversed biased p-n junction between the floating body **424** and the collector n+ region **416** may cause a small current to flow across the junction. Some of the current may be in the form of hot carriers accelerated by the electric field across the

junction. These hot carriers may collide with atoms in the semiconductor lattice which may generate hole-electron pairs in the vicinity of the junction. The electrons may be swept into the collector n+ region 416 by the electric field, while the holes may be swept into the floating body region 424.

The hole current flowing into the floating region 424 (usually referred to as the base current) will maintain the logic-1 state data. The efficiency of the refresh operation can be enhanced by designing the bipolar device formed by collector n+ region 416, floating region 424, and emitter region 418 to be a low-gain bipolar device, where the bipolar gain is defined as the ratio of the collector current flowing out of collector n+ region 416 to the base current flowing into the floating region 424.

FIG. 4C is a drawing illustration of the energy band diagram of the intrinsic n-p-n bipolar device 430 when the floating body region 424 is positively charged and a positive bias voltage is applied to the collector n+ region 416. The dashed lines indicate the Fermi levels in the various regions of the n-p-n transistor 430. The Fermi level is located in the band gap between the solid line 417 indicating the top of the valance band (the bottom of the band gap) and the solid line 419 indicating the bottom of the conduction band (the top of the band gap) as is well known in the art. The positive charge in the floating body region lowers the energy barrier of electron flow into the base region. Once injected into the floating body region 424, the electrons will be swept into the collector n+ region 416 due to the positive bias applied to the collector n+ region 416. As a result of the positive bias, the electrons may be accelerated and create additional hot carriers (hot hole and hot electron pairs) through an impact ionization mechanism. The resulting hot electrons flow into the collector n+ region 416 while the resulting hot holes will subsequently flow into the floating body region 424. This process restores the charge on floating body 424 and will maintain the charge stored in the floating body region 424 which will keep the n-p-n bipolar transistor 430 on for as long as a positive bias is applied to the collector n+ region 416.

If floating body 424 is neutrally charged (the voltage on floating body 424 being equal to the voltage on grounded emitter region 418), a state corresponding to logic-0, no appreciable current will flow through the n-p-n transistor 430. The bipolar device 430 will remain off and no appreciable impact ionization occurs. Consequently memory cells in the logic-0 state will remain in the logic-0 state.

FIG. 4D shows the energy band diagram of the intrinsic n-p-n bipolar device 430 when the floating body region 424 is neutrally charged and a bias voltage is applied to the collector n+ region 416. In this state the energy level of the band gap bounded by solid lines 417A and 419A is different in the various regions of n-p-n bipolar device 430. Because the potential of the floating body region 424 and the emitter region 418 is substantially equal, the Fermi levels are constant, resulting in an energy barrier between the emitter region 418 and the floating body region 424. Solid line 423 indicates, for reference purposes, the energy barrier between the emitter region 418 and the floating body region 424. The energy barrier prevents electron flow from the emitter region 418 to the floating body region 424. Thus the n-p-n bipolar device 430 will remain off.

FIG. 4E is a drawing illustration of an exemplary refresh operation in an exemplary array 480 formed by a plurality of memory cell 450 (corresponds to a memory layer of the 3D DRAM device, such as those described herein) is shown in FIG. 4E. Present in FIG. 4E are word lines (WLs) 470a

through 470n, source lines (SLs) 472a through 472n, and bit lines (BLs) 474a through 474p. In this example, each of the word lines 470a through 470n is associated with a single row of memory cells 450 and is coupled to the gate 460 of each memory cell 450 in that row. Similarly, each of the source lines 472a through 472n is associated with a single row of memory cells 450 and is coupled to the collector n+ region 416 of each memory cell 450 in that row. Each of the bit lines 474a through 474p is associated with a single column of memory cells 450 and is coupled to the emitter region 418 of each memory cell 450 in that column. In this exemplary refresh operation, there is no individually selected memory cell. Rather cells are selected in rows by the source lines 472a through 472n and may be selected as individual rows, as multiple rows, or as all of the rows comprising array 480. Cells can also be selected in columns by bit lines 474a through 474p and may be selected as individual columns, as multiple columns, or as all of the columns comprising array 480.

Persons of ordinary skill in the art will appreciate that while exemplary array 480 is shown as a single continuous array in FIG. 4E, that many other organizations and layouts are possible like, for example, word lines may be segmented or buffered, bit lines may be segmented or buffered, source lines may be segmented or buffered, the array 480 may be broken into two or more sub-arrays, control circuits such as word decoders, column decoders, segmentation devices, sense amplifiers, write amplifiers may be arrayed around exemplary array 480 or inserted between sub-arrays of array 480. Thus the exemplary embodiments, features, design options, etc., described are not limiting in any way.

Also shown in FIG. 4E are multiplexers 440a through 440n and voltage waveforms 442a through 442n. A constant positive bias can be applied to the collector n+ regions 416 of memory cells 450 (through SL terminal 472). Alternatively, a periodic pulse of positive voltage can be applied to the collector n+ regions 416 of memory cells 450 through SL terminal 472 as opposed to applying a constant positive bias to reduce the power consumption of the memory cell 450. FIG. 4E further shows multiplexers 440a through 440n each coupled to one of the source lines 472a through 472n that determine the bias voltages applied to SL terminals 472a through 472n, which will be determined by different operating modes. The pulsing of the voltage on the SL terminals may be controlled, for example, by applying pulses of logic signals such as, for example, waveforms 442a through 442n to the select input of multiplexers 440a through 440n thereby selecting, for example, ground (0.0 volts) or a power supply voltage such as V_{CC} . Many other techniques may be used to pulse the voltage applied to SL terminals 472a through 472n such as, for example, applying the waveforms 442a through 442n at different times, or applying them simultaneously, or coupling the select inputs of multiplexers 442a through 442n together and applying a single pulsed waveform to all of the multiplexers 442a through 442n simultaneously (not shown in the figure). Many other options will readily suggest themselves to persons of ordinary skill in the art. Thus the described exemplary embodiments are not limiting in any way.

FIG. 4F is a drawing illustration of another method to provide voltage pulses to SL terminals 472a through 472n of exemplary array 480 of memory cells 450. The positive input signals to multiplexers 440a through 440n may be generated by voltage generator circuits 444a through 444n coupled to one input of each of the multiplexers 440a through 440n. Alternatively, a single voltage generator circuit may be coupled to each of the multiplexers 440a

through 440n reducing the amount of overhead circuitry required to refresh the memory cells 450 of array 480. Other embodiments are possible including, for example, applying the waveforms 442a through 442n at different times, or applying them simultaneously, or coupling the select inputs of multiplexers 442a through 442n together and applying a single pulsed waveform to all of the multiplexers 442a through 442n simultaneously (not shown in the figure).

FIG. 4G is a drawing illustration of a reference generator circuit suitable for use as reference generator circuits 444a through 444n in FIG. 4F. The reference generator includes reference cell 453, which may consist of a modified version of memory cell 450 described above with region 425 of p-type conductivity. The p-type region 425 allows for a direct sensing of the floating body region 424 potential. P-type region 425 is drawn separately even though it has the same conductivity type as floating body region 424 because it may be doped differently, such as, for example, a higher concentration of doping than floating body region 424, to facilitate contacting it. The reference cell 453 for example can be configured to be in state logic-1 where the potential of the floating body region 424 is positive, for example at +0.5V. The potential sensed through the p-type region is then compared with a reference value V_{REF} , e.g. +0.5V, by operational amplifier 427. If the potential of the floating body region 424 is less than the reference value, the voltage applied to the SL terminal 472 (which is connected to drain n+ region 416 of the reference cell 453 and is also connected to collector n+ region 416 of the memory cell 450) may be increased by operational amplifier 427 until the potential of the floating body region 424 reaches the desired reference voltage. If the potential of the floating body 424 region is higher than that of the reference value, the voltage applied to SL terminal 472 can be reduced by operational amplifier 427 until the potential of the floating body region 424 reaches the desired reference voltage. Reference voltage V_{REF} may be generated in many different ways such as, for example, using a band gap reference, a resistor string, a digital-to-analog converter, and so on. Similarly alternate voltage generators of types known in the art may be used.

Also shown in FIGS. 4E and 4F, read circuitry 499a may be coupled to the bit line 474a. In some embodiments, a reading circuit 499b through 499p (not shown in FIGS. 4E and 4F) may be coupled to each bit of the bit lines 474b through 474p, while in other embodiments reading circuit 499a may be shared between multiple columns using a decoding scheme (not shown).

FIG. 5A is a drawing illustration of another embodiment of a gateless memory cell 5150 in a memory layer of the 3D DRAM device. FIG. 5B is a drawing illustration of the equivalent circuit representation of the memory cell shown in FIG. 5A. Similar to memory cell 450 shown in FIG. 4A, memory cell 5150 includes a floating body 524 of p-type conductivity. The floating body 524 is bounded by the insulator layer 522, n+ regions 516 and 518, and by the insulator layer 526. A difference to the memory cell 450 shown in FIG. 4A is that no gate electrode exists in memory cell 5150. The n+ regions 516 and 518 may be configured differently, for example, the n+ region acting as the emitter region (n+ region 518) is typically more heavily doped than the n+ collector region (n+ region 516).

As shown in FIG. 5B, floating body DRAM cell 5150 may include an n-p-n bipolar device 5130, n-p-n bipolar device 5130 may include n+ region 516 (the collector region), floating body 524 (the base region), and n+ region 518 (the emitter region). The collector region can be connected to the

SL terminal 572 and the emitter region can be connected to the BL terminal 574, or vice versa.

FIG. 5C is a drawing illustration of an exemplary memory array 5180 which will be used in subsequent drawing figures to illustrate the various operations that may be performed on memory cell 5150 when arranged in an array to create a memory device. Memory array 5180 comprises in part representative memory cells 5150a, 5150b, 5150c, and 5150d. In operations where a single memory cell is selected, representative memory cell 5150a will represent the selected cell while the representative memory cells 5150b, 5150c, and 5150d will represent the various cases of unselected memory cells sharing a row, sharing a column, or sharing neither a row nor a column respectively with selected representative memory cell 5150a. Similarly in the case of operations performed on a single row or column, representative memory cell 5150a will be on the selected row or column.

The memory cell states are represented by the charge in the floating body 524, which modulates the intrinsic n-p-n bipolar device 5130. The collector region can be connected to the SL terminal 572 and the emitter region can be connected to the BL terminal 574, or vice versa. If cell 5150 has a substantial number of holes stored in the body region 524, then the memory cell may have a higher bipolar current (e.g. current flowing from BL to SL terminals during read operation) compared to if cell 5150 does not store an appreciable amount of holes in body region 524.

The positive charge stored in the body region 524 may decrease over time due to the p-n diode leakage formed by floating body 524 and n+ regions 516 and 518, and due to charge recombination. A refresh operation applied to the entire memory array 5180 is illustrated in FIG. 5D. The refresh operation on memory cell 5150 can be performed by applying a positive bias to the collector region 516 (connected for example to SL terminal 572) while grounding the emitter region 518 (connected for example to BL terminal 574). If floating body 524 is substantially positively charged (i.e. in a state logic-1), the n-p-n bipolar transistor 5130 will be turned on.

A fraction of the bipolar transistor 5130 current will then flow into floating body region 524 and maintain the state logic-1 data. The efficiency of the refresh operation can be enhanced by designing the bipolar transistor 5130 to be a low-gain bipolar device, where the bipolar gain is defined as the ratio of the collector current flowing out of collector region 516 to the base current flowing into floating body region 524.

For memory cells in state logic-0 data, the bipolar device will not be turned on, and consequently no appreciable base hole current will flow into floating region 524. Therefore, memory cells in state logic-0 will remain in state logic-0.

A periodic pulse of positive voltage can be applied to the SL terminal 572 as opposed to applying a constant positive bias to reduce the power consumption of the memory cell 5150.

In the entire array refresh operation of FIG. 5D, source line terminals 572a through 572n may be biased at +1.2V and bit lines 574a through 574p may be biased to 0.0V. This refreshes substantially all of the cells in memory array 5180.

A single row operation can also be performed on memory array 5180 as illustrated in FIG. 5E, where selected source line terminal 572a may be biased at +1.2V while the unselected source line terminals 572b (not shown) through 572n may be biased at $V_{dd}/2$, and bit lines 574a through 574p may be biased to 0.0V. This refreshes substantially all of the selected cells in memory array 5180.

A single memory cell read operation is illustrated in FIG. 5F. The read operation for memory cell 5150a, for example, can be performed by sensing the current of the bipolar device 5130 by applying a positive voltage to the selected BL terminal 574a and zero voltage to the selected SL terminal 572a. The positive voltage applied to the selected BL terminal may be less than or equal to the positive voltage applied to the SL terminal during the refresh operation. The unselected BL terminals may remain at V_{dd}/2 and the unselected SL terminals may remain at a positive voltage.

FIG. 5F shows the bias condition for the selected memory cell 5150a and unselected memory cells 5150b, 5150c, and 5150d in memory array 5180. In this particular non-limiting embodiment, about 0.0 volts may be applied to the selected SL terminal 572a while about +1.2V is applied to the unselected source line terminals 572b (not shown) through 572n, about +1.2 volts is applied to the selected BL terminal 574a while 0.0V is applied to the unselected bit line terminals 574b through 574p. These voltage levels are exemplary only and may vary from embodiment to embodiment.

Current will flow through intrinsic bipolar device 5130 if the floating body is substantially positively charged and no current to flow if the floating body is substantially discharged since the bipolar device 5130 is off. As described above, the n+ regions 516 and 518 can be configured asymmetrically such that the current flowing through the selected cell 5150a during read operation (from the BL terminal 574 to the SL terminal 572) may be higher than the refresh current flowing through the unselected memory cells (from the SL terminal 572 to the BL terminal 574), although similar bias conditions are applied to selected and unselected memory cells 5150 (with the bias conditions are reversed between the BL and SL terminals of the selected and unselected memory cells 5150).

For memory cell 5150b sharing the same row as the selected memory cell 5150a, the SL terminal 572a and the BL terminal 574p are both biased to 0.0V and consequently these cells will not be at the refresh mode. However, because read operation is accomplished much faster (in the order of nanoseconds) when compared to the lifetime of the charge in the floating body 524 (in the order of milliseconds), it should cause little disruption to the charge stored in the floating body.

For memory cell 5150c sharing the same column as the selected memory cell 5150a, a positive voltage is applied to the BL terminal 574a and SL terminal 572n. No base current will flow into the floating body 524 because there is no appreciable potential difference between SL terminal 572 and BL terminal 574 (i.e. the emitter and collector terminals of the n-p-n bipolar device 5130). However, because the read operation is accomplished much faster (in the order of nanoseconds) compared to the lifetime of the charge in the floating body 524 (in the order of milliseconds), it should cause little disruption to the charge stored in the floating body.

For memory cell 5150d sharing neither the same row nor the same column as the selected memory cell 5150a, both the SL terminal 572n will remain positively charged and the BL terminal 574p may remain grounded. Representative memory cell 5150d will be in the refresh mode, where memory cells in state logic-1 will maintain the charge in floating body 524 because the intrinsic bipolar device 5130 will generate hole current to replenish the charge in floating body 524, while memory cells in state logic-0 will remain in neutral state.

The various voltage bias levels above are exemplary only. They will vary from embodiment to embodiment as a function of both design choice and the process technology used.

FIG. 5G illustrates a single row write logic-0 operation. In FIG. 5G the selected row SL terminal 572a may be biased negatively at about -0.5V while the unselected row SL terminals 572b (not shown) through 572n may be biased at about +1.2V and all the BL terminals 574a through 574p may be biased at 0.0V. This causes the selected cells such as representative memory cells 5150a and 5150b to have their bipolar devices turn on due to forward bias on the floating body 524 to collector region 516, thereby evacuating the holes from the floating body 524.

For the unselected rows (which in this case is all the memory cells 5150 in memory array 5180 not on the selected row), the SL terminal 572 is at +1.2V and the BL terminal 574 is at 0.0V, which corresponds to the refresh operation described above.

A write logic-0 operation can also be performed on a column basis by applying a negative bias to the BL terminal 574 as opposed to the SL terminal 572. The SL terminal 572 will be zero or positively biased. Under these conditions, substantially all memory cells sharing the same BL terminal 574 will be written into state logic-0 and substantially all the other cells will be in the refresh operation.

The various voltage bias levels above are exemplary only. They will vary from embodiment to embodiment as a function of both design choice and the process technology used.

A write logic-1 operation can be performed on memory cell 5150 through an impact ionization mechanism as described in FIG. 5H. An example of the bias condition of the selected memory cell 5150a under impact ionization write logic-1 operation is illustrated in FIG. 5H. A positive bias may be applied to the BL terminal 574, while zero voltage may be applied to the selected SL terminal 572. The positive bias applied to the BL terminal 574 may be greater than the positive voltage applied to the SL terminal 572 during refresh operation. The positive bias applied to the BL terminal is large enough to turn on bipolar device 5130 regardless of the initial state of the data in selected memory cell 5150a. This results in a base hole current to the floating body 524 of the selected memory cell 5150a charging it up to a logic-1 state.

In one particular non-limiting embodiment, the following bias conditions may be applied to the selected memory cell 5150a: a potential of about 0.0 volts is applied to selected SL terminal 572a and a potential of about +2.0 volts is applied to selected BL terminal 574a. The following bias conditions may be applied to the unselected terminals: about +1.2 volts is applied to SL terminals 572b (not shown) through 572n, and about 0.0 volts is applied to BL terminals 574b through 574p. FIG. 5H shows the bias condition for the selected and unselected memory cells in memory array 5180. The various voltage bias levels above are exemplary only. They will vary from embodiment to embodiment as a function of both design choice and the process technology used.

For representative memory cell 5150b sharing the same row as the selected memory cell 5150a, SL terminal 572a and BL terminal 574p may be grounded. Bipolar device 5130 will be off and the memory cell 5150b will not be at the refresh mode. However, because write operation is accomplished much faster (in the order of nanoseconds) compared to the lifetime of the charge in the floating body 524 (in the order of milliseconds), it should cause little disruption to the charge stored in the floating body.

For representative memory cell **5150c** sharing the same column as the selected memory cell **5150a**, a greater positive voltage is applied to the BL terminal **574a** and a lesser positive voltage is applied to SL terminal **572n**. Less base current will flow into the floating body **524** than in selected memory cell **5150a** because of the lower potential difference between SL terminal **572** and BL terminal **574** (i.e. the emitter and collector terminals of the n-p-n bipolar device **5130**). However, because the write operation is accomplished much faster (in the order of nanoseconds) compared to the lifetime of the charge in the floating body **524** (in the order of milliseconds), it should cause little disruption to the charge stored in the floating body.

For representative memory cell **5150d** sharing neither the same column nor the same row as the selected memory cell **5150a**, the SL terminal **572** is positively charged and the BL terminal is grounded. Representative memory cell **5150d** will be at refresh mode, where memory cells in state logic-1 will maintain the charge in floating body **524** because the intrinsic bipolar device **5130** will generate hole current to replenish the charge in floating body **524** and where memory cells in state logic-0 will remain in neutral state.

The various voltage bias levels above are exemplary only. They will vary from embodiment to embodiment as a function of both design choice and the process technology used. Also, the first conductivity type may be changed from p-type to n-type and the second conductivity type may be changed from n-type to p-type, and the polarities of the applied biases may be reversed. Thus the invention is not to be limited in any way except by the appended claims.

An important feature of a DRAM device is a low refresh rate. It is even desirable if a two stable states memory could be achieved without interfering with the memory access for read and write, as it would remove the necessity of a refresh operation. Such a memory could be called SRAM (Static Random Access Memory). There are some 2D structures that presented such type of memories; for example, K. Sakui, T. Hasegawa, T. Fuse, S. Watanabe, K. Ohuchi, and F. Masuoka, "A new static memory cell based on the reverse base current effect of bipolar transistors," IEEE Trans. Electron Devices, vol. 36, no. 6, pp. 1215-1217, June 1989; M. Reisch, "On bistable behavior and open-base breakdown of bipolar transistors in the avalanche regime—Modeling and applications," IEEE Trans. Electron Devices, vol. 39, no. 6, pp. 1398-1409, June 1992; and US Patent Publication No. 2012/0230123 "Method of Maintaining the State of Semiconductor Memory Having Electrically Floating Body Transistor". These three documents are incorporated by reference herein in their entirety.

FIG. 6 is a drawing illustration of a Floating Body memory cell **50** with a buried well region **12**, where applying a back bias (through terminal **78**) to the n-type buried well region **12** (also referred to as the back bias region **12**) may maintain the charge stored in the floating body region **24**. FIG. 6 may be found as FIG. 1A of the US Patent Publication No. 2012/0230123. The floating body **24** may be P type, the drain **16** and source **18** may be N type, the gate oxide **62** and the gate **60** may include, such as, for example, SiO₂ and polysilicon or HKMG, and the floating body transistor may be isolated by deep trench isolations **26**. The user terminals for writing and reading the memory may be drain **72**, source **74**, and gate **70**. The top surface **14** of the mono-crystal may be the upper side of the wafer. Interconnect layers, such as is known by those skilled in the art, may be formed to connect the memory cell (not shown). A key to the two charge states holding of the floating body memory is the application of a positive back bias, such as 1.2 volt, to

the back bias region **12** (through terminal **78**). The NPN bipolar transistor formed between the n-type back bias region **12**, the p-type floating body region **24**, and the n-type drain **16** or source **18** is the key to the unique charging mechanism as described in these referenced art and before in respect to at least FIGS. 4A, 4B, 5A and 5B. A key to the self-charging mechanism, as had been detailed in the referenced art, is having the structure meet the formula $(M-1)*\beta-1$, which is related to the structure feature and design of the memory cell **50**, where β is the gain of the bipolar transistor and M is the impact ionization multiplication factor.

In the following we present a 3D RAM architecture having two stable states, the two stable states may be two stable floating body charge levels. The structure and process flow have similarities to a previous description, such as FIGS. 3A-K and associated text. A device and method to form back-bias region for 3D floating body memory architecture is described below.

As illustrated in FIGS. 7A, 7B, 7C, and 7D, FIG. 7A is a drawing illustration of an embodiment of a three-dimensional view of a 3D RAM structure and device architecture prior to the interconnect stage of the process flow (similar to FIG. 7G), FIG. 7B is a drawing illustration of cross-sectional cut I of FIG. 7A, FIG. 7C is a drawing illustration of cross-sectional cut II of FIG. 7A, and FIG. 7D is a drawing illustration of cross-sectional cut II of FIG. 7A with the gate material and perforated gate dielectric overlap/under-lap depicted. FIGS. 7A, 7B, 7C, and 7D may include n+ silicon regions **728**, silicon oxide regions **722**, gate regions **760**, back-bias regions **712**, gate dielectric regions **762**, p- channel regions **724**, isolation dielectric **706**, gate dielectric openings **711**, and peripheral circuits **702**. FIG. 7D may include a shadowed overlay image of gate regions **760** and gate dielectric openings **711** depicting the overlap and underlaps of these regions with respect to p- channel regions **724**. FIG. 7B may include surface **713**, wherein back-bias region **712** may be in physical contact and make electrical connection to p- channel region **724**.

A floating body transistor in the stack may include a single side gate (gate regions **760**) on one side of floating body p- channel region **724** and a back-bias region **712** formed on the other side of the floating body p- channel region **724**. Gate region **760** may be insulated from the floating body p- channel region **724** with a gate dielectric regions **762**, yet still modulate the channel. In this case the back-bias is not horizontal such as in FIG. 4A but rather vertical such as back bias regions **712** of FIG. 7B. N+ silicon regions **728** may be connected and utilized as either a source or drain to help form the two stable states floating body transistor.

A process flow that may be utilized to form the structure shown in FIGS. 7A-7D is described as follows. Many steps may be similar to those used to form the structure shown in FIG. 3E.

As illustrated in FIG. 7E, multiple mono-crystalline p-silicon layers may be formed with silicon oxide layers in-between and then lithography and etch processes may be utilized to make a structure, such as, for example, as shown in FIG. 7E. Thus p-silicon regions **721** and silicon oxide regions **722** may be stacked and formed above peripheral circuits **702**. Processes to form the structure in FIG. 7E may include the steps described with respect to FIGS. 3A to 3E herein. Peripheral circuits **702** may be constructed with tungsten, or conventional aluminum/copper, wiring and may have isolation and/or bonding oxide above it (in-between the top metallization/wiring of peripheral circuits **702** and the bottom p-silicon region in the stack, such as isolation oxide

706. The composition of the silicon oxide regions 722 within the stacked Si/SiO₂ layers may be insulators or dielectrics other than silicon dioxide such as, for example, a low-k dielectric, carbon containing silicon oxides, amorphous carbon. The thickness of silicon oxide regions 722 within the stacked Si/SiO₂ layers may be adjusted to minimize layer to layer, strata to strata disturb mechanisms, and may include thicknesses of 50 nm, 75 nm, 100 nm, 150 nm, 200 nm, 500 nm, and less than 1000 nm. A thin conductive layer, such as a metal, may also be formed between the two bonding oxides to form a field shield to mitigate layer to layer, strata to strata disturb mechanisms, and may be electrically floating or tied to a bias, such as ground or Vdd. The stacked Si/SiO₂ layers may alternatively be formed by successive ion implants of oxygen atoms/ions to various depths from the top surface of a mono-crystalline silicon wafer/substrate and then heat treated to form oxide layers thus forming silicon layers in-between the oxide layers, a layered 'SIMOX' process approach.

As illustrated in FIG. 7F, a perforated gate dielectric layer 762 (partially shown for clarity) may be formed which has gate dielectric openings 711 on one face of the p-silicon 721 and silicon oxide 722 layer stack, a gate electrode material may be deposited and CMP'd substantially to the top of the Si/SiO₂ stack. The gate dielectric may be grown on the exposed surfaces of p-silicon regions 721 (for example, with the TEL SPA tool radical oxidation oxide) or deposited substantially over the structure's surface, such as, for example, in the well-known HKMG formation processing, a lithographic step and etch of the deposited gate dielectric may thus form perforated gate dielectric layer 762 and gate dielectric openings 711 on one face of the p-silicon 721 and silicon oxide 722 layer stack and leave the gate dielectric intact another face of the p-silicon 721 and silicon oxide 722 layer stack. A gate electrode material, such as, for example, doped amorphous or polysilicon, or the well-known metal stack of HKMG processing, may be deposited, thus bringing the conductive gate electrode material in direct contact and electrical connection with exposed faces of the p-silicon 721, and forming a field effect device of gate electrode influence thru the gate dielectric of the eventual transistor p-channel regions 724 formed by portions of p-silicon 721 layers. The gate electrode material may be in-situ doped during deposition, or doped at a later step. CMP may be performed to planarize the gate electrode material. The top face of the topmost silicon oxide region 722 may have an etch stop/CMP stop material, such as, for example, SiN or a-carbon, placed on it at an earlier stage, so to provide a CMP stop, thus enabling the formation of separate gate and back bias control regions. Although the width of the p-regions 721 near and under the gates are illustrated as being larger than the thickness, one skilled in the art would recognize that the reverse (i.e., thickness larger than width) could be formed to provide increased gate control of the transistor channel.

As illustrated in FIG. 7G, n+ silicon regions 728, gate regions 760 and back-bias regions 712 may be formed. The gate may be lithography defined. The widths of the gate structure regions and the gate dielectric openings 711 may be designed such that the gate structure regions will substantially always overlap the gate dielectric openings 711. Using the remaining photoresist of the gate structure regions lithography, portions of p-regions 721 not covered by the gate structure regions photoresist may be implanted to form n+ regions 728, and thus form p-channel regions 724. This multi-step implantation process may utilize different implant energies. The gate may then be etched to define gate

structure regions shown in FIG. 7G, thus forming gate regions 760 and back-bias regions 712, and the photoresist stripped. A thermal annealing step, such as an RTA or spike anneal or laser anneal or flash anneal, may be conducted to activate the n+ implanted doped regions. The optical anneal system, such as the laser, spike, flash anneals, may be utilized to crystallize any deposited polysilicon or amorphous silicon (which may be used as a gate electrode material depending on process design choice). The structure valleys may be filled with a dielectric (not shown for clarity), such as, for example, SACVD oxides, and then CMP'd substantially to or partially into the topmost silicon oxide layer 722 of the Si/SiO₂ stack, or substantially to or partially into the CMP/etch stop layer as previously discussed. Thus, horizontal floating gate transistors with separate gate and back bias control regions on the previously exposed sides of each p-transistor channel region, and horizontal select lines (as has been described before in connection to FIG. 3 herein, and in the incorporated patent references) may be formed in a stack configuration.

As illustrated in FIG. 7H, an inter-layer dielectric, such as, for example silicon oxide or doped silicon dioxides, may be deposited and planarized. For clarity, the silicon oxide layer is shown transparent. Contacts to gate regions 760 and the associated local metallization gate connectivity 750, as well as contacts to back-bias regions 712 and the associated local metallization back-bias connectivity 752 may be formed using known methods in the art.

As illustrated in FIG. 7I, Source-Line (SL) connectivity 754, such as contacts and metal lines, may be formed by etching and deposition using known methods in the art. These SL contacts may be shared among the layers of memory. Gate connectivity 750 and back-bias connectivity 752 are not shown in FIG. 7I for clarity. The bit lines (BL) 756 are shown as a portion of the n+ silicon regions 728. Bit line contacts may be formed, for example, as sidewall structures or end-wall structures, with various overlaps as required by the process and layout.

Further, using known methods in the art, gate connectivity 750 may be connected to form the WL—word select lines. Contacts may be made to BLs, WLs and SLs of the memory array at its edges. BL contacts can be made into stair-like structures using techniques described in "Bit Cost Scalable Technology with Punch and Plug Process for Ultra High Density Flash Memory," *VLSI Technology, 2007 IEEE Symposium on*, vol., no., pp. 14-15, 12-14 Jun. 2007 by Tanaka, H.; Kido, M.; Yahashi, K.; Oomura, M.; et al., following which contacts can be constructed to them. Formation of stair-like structures for BLs could be done in steps prior to FIG. 7I. Electrical connection to the underlying peripheral circuits may be accomplished with vertical conductive vias, for example, the thru layer via or thru silicon via processes and structures, which may be described in the incorporated patent references or known by those skilled in the art. In addition, thermal vias may be utilized to carry heat, whether from processing or from operation, away from the upper layer without harming the underlying metallization or devices.

FIG. 7J is a top view exemplary illustration of the floating body transistors sharing on one side of the Si/SiO₂ stacks (n+ regions 728 and floating body p-channel regions 724) gate regions 760 and on the other side of the Si/SiO₂ stacks back bias regions 712 connected to p-channel regions 724 in the openings of the perforated gate dielectric layer 762. The back-bias regions act as the collector of the bipolar charging transistor as illustrated in FIG. 4B. Bipolar transistors that utilize a polysilicon collector with monocrystalline base and

emitter are well known in the art to perform well. The contacts of the source line connectivity **754** are shown, but the metal lines, as well as the SL staircase and WL connectivity are not shown for clarity. Back-bias regions **712** may be mutually connected to a bias source.

Persons of ordinary skill in the art will appreciate that the illustrations in FIGS. 7A through 7J are exemplary only and are not drawn to scale. Such skilled persons will further appreciate that many variations are possible such as, for example, the Si/SiO₂ stack may be formed with the N+ and p- regions already formed by stacking with 1-mask per stack layer processing as described, for example, in FIG. 2 herein. Further, it may not be necessary to overlap the implant gate structure regions and the gate dielectric openings **711**. Moreover, perforated gate dielectric layer **762** may not need to be perforated, and control of the back-bias effects may be performed thru the gate dielectric from an efield influence modulated by the back bias regions **712**, or by band bending with an Esaki diode structure. Furthermore, peripheral circuits may be on top of the memory stack layers rather than on the bottom, and connected accordingly. Moreover, a prior to the n+ implant step anneal to repair damages that were formed during prior step such as layer transfer ion cut related damages and etch step related damages, may be performed. Furthermore, some of the memory global control lines could be implemented in the bottom base layer peripheral circuits **702** and connected to the upper memory structure as it is processed. This could be done for the back-bias connections. For example, instead of the back-bias connectivity **752** being formed after the memory stack, the base layers from the peripheral circuits **702** may provide the back-bias connection. In such case before depositing the gate electrode material, a contact to those connections would be etched in the soon to be back bias regions **712**. Many other modifications within the scope of the present invention will suggest themselves to such skilled persons after reading this specification. Thus the invention is to be limited only by the appended claims.

The impact ionization efficiency of the polysilicon collector in the architecture illustrated in FIGS. 7A-7D may typically be low (the (M-1) factor is typically less than 10⁻³). As a result, a large current may be required in the holding operation. Using FIG. 6 and its description as a guide, to further improve the efficiency of the holding operation, the source region (**16** of FIG. 6) or the drain region (**18** of FIG. 6), which may be either of the n+ regions **728** on the sides of p- channel regions **724**, may be used as the collector region/node and the polysilicon region, back bias region **712**, may now act as the emitter region/node. The holding operation is still governed by the n-p-n bipolar transistor formed by one of the source/drain regions **16** or **18** (n+ regions **728**), the floating body region **24** (p- channel regions **724**), and the polysilicon region **12** (back bias region **712**). The back-bias node employed in the holding operation may now be selected from one of the source/drain regions **16** or **18** (n+ regions **728**). The terminals used for accessing (i.e. reading and writing) the memory cell are now connected to the polysilicon region **12** (back bias region **712**), the other source/drain region **16** or **18** (n+ regions **728**) not used as the back-bias region, and the gate electrode **60** (gate regions **760**).

As illustrated in FIG. 7K, a dual port RAM may be constructed utilizing many of the concepts and flow of FIGS. 7A-7J. The processing may proceed to generate the structure of FIG. 7F (with some extra removal areas of the perforated gate oxide). At this point, the flow and processing described related to FIG. 7G may be utilized, but the lithographic

pattern to form the n+ implanted regions and the gate regions, back-bias regions, and mid-FB junction connection will be different. Using the remaining photoresist of the gate structure regions lithography, portions of p- regions **721** not covered by the gate structure regions photoresist may be implanted to form n+ regions **728**, and thus form a common p- channel region **724** that not only includes the region directly between gate regions **760** and back-bias regions **712**, but also between those regions so to form a commoned p- region (indicated on the topmost silicon layer in the drawing where visible), which will be the common floating body. Additionally, the photolithography pattern may include covering the gate fill area which may become mid-FB junction connection **792**. Mid-FB junction connection **792** may directly connect to the common floating body p- channel region **724** in the common location (between the gate/body-bias pairs) as that side wall face may be opened up in the earlier formation of perforated gate dielectric **762** at gate dielectric openings **711** (in a similar fashion as the back-bias regions **712**). Gate connectivity, back-bias connectivity, mid-FB junction connection, and BL connectivity may then be formed using well known techniques to those skilled in the art. Mid-FB junction connection **792** may include an opposite conductivity type doping than that of common floating body p- channel region **724** so to form a junction connection at the related gate dielectric opening **711**.

FIG. 7L is a top view exemplary illustration of the dual port RAM floating body transistors sharing on one side of the Si/SiO₂ stacks (n+ regions **728** and commoned floating body p- channel regions **724**) gate regions **760** and on the other side of the Si/SiO₂ stacks back bias regions **712** and mid-FB junction connection **792** connected to commoned floating body p- channel regions **724** in the openings of the perforated gate dielectric layer **762**. The back-bias regions act as the collector of the bipolar charging transistor as illustrated in FIG. 4B.

As illustrated in FIG. 7M, a dual port RAM with integrated select transistors may be constructed utilizing many of the concepts and flow of FIGS. 7A-7L. The processing may proceed to generate the structure of FIG. 7F (with some extra removal areas of the perforated gate oxide). At this point, the flow and processing described related to FIG. 7G may be utilized, but the lithographic pattern to form the n+ implanted regions and the gate regions, back-bias regions, select gates, and mid-FB junction connection will be different. Using the remaining photoresist of the gate structure regions lithography, portions of p- regions **721** not covered by the gate structure regions photoresist may be implanted to form n+ regions **728**, and thus form a common p- channel region **724** that not only includes the region directly between gate regions **760** and back-bias regions **712**, but also between those regions so to form a commoned p-region (indicated on the topmost silicon layer in the drawing where visible), which may be the common floating body. The p- channel regions of the select transistor gates **796** may also be masked off from the implants. Additionally, the photolithography pattern may include covering the gate fill area which will become mid-FB junction connection **792**. Mid-FB junction connection **792** may directly connect to the p- channel region **724** in the common location (between the gate/body-bias pairs) as that side wall face is opened up in the earlier formation of perforated gate dielectric **762** at gate dielectric openings **711** (in a similar fashion as the back-bias regions **712**). The select gates may have the perforated gate dielectric **762** between the gate and the channel. Gate connectivity, back-bias connectivity, select gate connec-

tions, mid-FB junction connection, and BL connectivity may then be formed using well known techniques to those skilled in the art. Mid-FB junction connection **792** may include an opposite conductivity type doping than that of common floating body p- channel region **724** so to form a junction connection at the related gate dielectric opening **711**.

FIG. 7N is a top view exemplary illustration of the dual port RAM with integrated select transistors wherein the floating body transistors are sharing on one side of the Si/SiO₂ stacks (n+ regions **728** and floating body p- channel regions **724**) gate regions **760** and on the other side of the Si/SiO₂ stacks back bias regions **712** and mid-FB junction connection **792** connected to commoned p- channel regions **724** in the openings of the perforated gate dielectric layer **762**. The back-bias regions act as the collector of the bipolar charging transistor as illustrated in FIG. 4B. The select gates **796**, double gated around the associated channel region of p- channel regions **724**, may be utilized to control access to the floating body transistor on that level and region of the stack.

As illustrated in FIG. 8, another embodiment of the 3D RAM architecture having two stable states wherein in the top mono-crystalline layer at least one of the two devices within the source lines of that layer may include an access device. Access transistor **820** may be connected in series to the floating body transistor selected to achieve an improved read and write access time. Second access transistor **821** may also be utilized in parallel with access transistor **820** for more access current when connected to the BL **878** as shown, or may function as another floating body device bit if connected to its own SL (not shown). The construction of the architecture may be similar to the structure described in FIGS. 7A-7J, with modifications described below.

Floating body transistors **870**, **871**, **872**, and **873** may overlay each other and be connected to corresponding Select or Source Lines **850**, **851**, **852**, and **853** respectively. The select lines may be formed by the N+ mono-crystalline layers of source lines (SL) **756** as described in FIG. 7. Overlying the floating body transistors may be access transistor **820** which may be connected to the floating body transistors, such as floating body transistors **873**, **872**, **871**, **870**, by the deep contact connection **836**. Deep contact connection **836** may be the deep contact portion of bit line connectivity **754** described in FIG. 7I. Access transistor **820** may share the same gate connection, Word Line **842** as the floating body transistors on the stack below it, such as floating body transistors **870**, **871**, **872**, and **873**. Floating body transistors **870**, **871**, **872**, and **873** may be selected by their source line connections Select or Source Lines **850**, **851**, **852**, and **853** respectively. As well, floating body transistors **874**, **875**, **876**, and **877** may be selected by their corresponding source line connections and accessed by the bit line **878** thru access transistor **820**, second access transistor **821**, or a combination of both access transistor. The read and write signal to the selected floating body may be transferred via the serially connected access transistor, such as access transistor **820**, resulting in a shorter write or read cycle.

During the read operation, the access transistors of the unselected word lines are turned off, for example by applying 0.0 volt. As a result, the leakage path due to the unselected memory cells in the unselected word lines are prevented by being disconnected from the bit line **878**. The leakage currents, if the leakage path is not disconnected, in a large density memory array (as expected from a 3D architecture) may be large enough to slow down or even disrupt the sensing operation of the sense amplifier.

Persons of ordinary skill in the art will appreciate that the illustration in FIG. 8 is exemplary only and is not drawn to scale. Such skilled persons will further appreciate that many variations are possible such as, for example, the access transistors could be constructed on the first mono-crystalline layer (layer closest to the peripheral circuits) and directly connected to the bit line control from the peripheral circuits below. Furthermore, by rearranging the stacked structure single mask layer etch layout geometry, a separate access device and floating body device on each layer could be constructed and accessed. Many other modifications within the scope of the present invention will suggest themselves to such skilled persons after reading this specification. Thus the invention is to be limited only by the appended claims.

Forming the peripheral circuitry on top of (or 'above') the memory stack fabric is an additional embodiment. For example, the techniques illustrated in FIG. 22F herein illustrate the formation of peripheral circuits **2298** on top of the memory fabric. Such could be used for the memory fabric described in relation to FIG. 7A to FIG. 7J. In some cases it might be desirable to have peripheral circuits both underneath the memory fabric and above it, using techniques describe herein or in the other patents incorporated by reference. An additional embodiment includes wherein the memory fabric is first built on an SOI wafer as has been described in respect to illustrations of FIG. 19 and FIG. 20 herein. The 3D memory fabric may be first formed and both top and bottom surfaces could be used for a deep connection etch and both surfaces could be used to form the memory control lines such as bit-lines, and then the peripheral circuits could be formed on one of both surfaces utilizing the 3D techniques described here and or in the patents incorporated herein.

An important advantage of the two stable states memory is in respect to low power standby operation. When the device is placed into standby, the back bias voltage could be dropped to about 50% of V_{cc}, for example, about 0.8 volt. Other combinatorial circuits could be disconnected from the power for further reduction of power consumption. As normal operation resumes, the voltage of the power supply and that of the back-bias would be brought up to standard levels and the circuit could resume normal operation. This is one way in which power consumption could be reduced without losing the data stored in the memory.

In some cases it might be advantageous to use laser or other annealing techniques to further improve the quality of the polysilicon by re-crystallization. Another alternative is to deposit the polysilicon with no doping or p type doping, and then perform an implant step to dope the polysilicon with N doping at the desired depth. Depth control of ion implantation is quite accurate which could be an important advantage for very thin layers and stacks. Activation could be done before low melting point metals, such as, for example, copper and aluminum, get deposited, and activation could be done for many layers simultaneously as discussed before. Use of optical anneal techniques to activate dopants in the Si/SiO₂ memory stack may also be employed to minimize damage to the underlying metallization.

As illustrated in FIG. 9, an embodiment wherein a two stable states memory may be formed with the back bias region that is formed in the same mono-crystalline layer/region as the floating body channel. The back bias region **912** may be spaced apart from the source region **916** and the drain region **918**, and lie in the same mono-crystalline layer **908**. The holding operation is performed through the n-p-n bipolar transistor formed by the source region **916**, floating body region **924**, and the back bias region **912**. In this

embodiment, the back bias region **912** is formed in the same mono-crystalline layer that includes the floating body transistor (formed by the source region **916**, drain region **918**, and the gate region **960** with gate dielectric **962**), wherein the floating body region **24** may be storing the charge. Gate region **960** (including gate connectivity **970**) and gate dielectric **962** are shown in dashes indicating shadowed, wherein they both overlap and form side gates on both illustrated layers of mono-crystalline material. In this illustration, mono-crystalline layer **908** may have a 3-side gate and the mono-crystalline layer below a two sided gate. The mono-crystalline layers may be isolated by oxide dielectric layers **930** and isolation dielectric **906** which may be utilized to isolate, and form bonding, of the memory stack to the peripheral circuits **902**. Drain regions **918** may be commoned by deep drain contact **974** and access to the source regions **916** may be accomplished by source connectivity **972**. Back-bias regions **912** may be accessed by bb connectivity **976**.

Section 2: Monolithic 3D Resistance-Based Memory

While many of today's memory technologies rely on charge storage, several companies are developing non-volatile memory technologies based on resistance of a material changing. Examples of these resistance-based memories include phase change memory, Metal Oxide memory, resistive RAM (RRAM), memristors, solid-electrolyte memory, ferroelectric RAM, MRAM, etc. Background information on these resistive-memory types is given in "Overview of candidate device technologies for storage-class memory," *IBM Journal of Research and Development*, vol. 52, no. 4.5, pp. 449-464, July 2008 by Burr, G. W.; Kurdi, B. N.; Scott, J. C.; Lam, C. H.; Gopalakrishnan, K.; Shenoy, R. S. Typical RRAM materials may include transition metal oxides such as TiOx, NiOx, HfOx, WoX, TaOx, VoX, CuOx, SrToOx, CuSiOx, SiOx, TiON, and electrodes may include Pt, TiN/Ti, TiN, Ru, Ni, W, TaN, Ir, Au. STT-MRAM materials may include Ir, PtMn, CoFe, Ru, CoFeB, MgO, CoFeB, Ta.

FIGS. **10A-J** describe a novel memory architecture for resistance-based memories, and a procedure for its construction. The memory architecture utilizes junction-less transistors and has a resistance-based memory element in series with a transistor selector. No mask is utilized on a "per-memory-layer" basis for the monolithic 3D resistance change memory (or resistive memory) concept shown in FIG. **10A-J**, and all other masks may be shared between different layers. The process flow may include several steps that occur in the following sequence.

Step (A): Peripheral circuits **1002** may be first constructed and above this an insulator layer, such as a layer of silicon dioxide, oxide layer **1004** may be deposited. FIG. **10A** shows a drawing illustration after Step (A).

Step (B): FIG. **10B** illustrates the structure after Step (B). A wafer of n+Silicon **1008** may have an oxide layer **1006** grown or deposited above it. Following this, hydrogen may be implanted into the n+Silicon wafer at a certain depth indicated by **1014**. Alternatively, some other atomic species such as Helium could be (co-)implanted. This hydrogen implanted n+Silicon wafer **1008** may form the top layer **1010**. The bottom layer **1012** may include the peripheral circuits **1002** with oxide layer **1004**. The top layer **1010** may be flipped and bonded to the bottom layer **1012** using oxide-to-oxide bonding.

Step (C): FIG. **10C** illustrates the structure after Step (C). The stack of top and bottom wafers after Step (B) may be cleaved at the hydrogen plane **1014** using either an anneal or a sideways mechanical force or other means. A CMP process may then be conducted. A layer of silicon oxide **1018** may then

be deposited atop the n+Silicon layer **1016**. At the end of this step, a single-crystal n+Si layer **1016** exists atop the peripheral circuits, and this has been achieved using layer-transfer techniques. Step (D): FIG. **10D** illustrates the structure after Step (D). Using methods similar to Step (B) and (C), multiple n+ silicon layers **1020** may be formed with silicon oxide layers in between. The composition of the silicon oxide regions within the stacked Si/SiO₂ layers may be insulators or dielectrics other than silicon dioxide such as, for example, a low-k dielectric, carbon containing silicon oxides, amorphous carbon. The thickness of the silicon oxide regions within the stacked Si/SiO₂ layers may be adjusted to minimize layer to layer, strata to strata disturb mechanisms, and may include thicknesses of 50 nm, 75 nm, 100 nm, 150 nm, 200 nm, 500 nm, and less than 1000 nm. A thin conductive layer, such as a metal, may also be formed between the two bonding oxides to form a field shield to mitigate layer to layer, strata to strata disturb mechanisms, and may be electrically floating or tied to a bias, such as ground or Vdd. The stacked Si/SiO₂ layers may alternatively be formed by successive ion implants of oxygen atoms/ions to various depths from the top surface of a mono-crystalline silicon wafer/substrate and then heat treated to form oxide layers thus forming silicon layers in-between the oxide layers, a layered 'SIMOX' process approach.

Step (E): FIG. **10E** illustrates the structure after Step (E). Lithography and etch processes may then be utilized to make a structure as shown in the figure.

Step (F): FIG. **10F** illustrates the structure after Step (F). Gate dielectric **1026** and gate electrode **1024** may then be deposited following which a CMP may be performed to planarize the gate electrode **1024** regions. Lithography and etch may be utilized to define gate regions. Gate dielectric **1026** and gate electrode **1024** may be, for example, a HKMG structure or a TEL SPA radical oxidation oxide and an appropriate work function electrode, for example, tungsten, degenerately doped polysilicon or amorphous silicon. Although the width of the n+ regions **1021** near and under the gates are illustrated as being larger than the thickness, one skilled in the art would recognize that the reverse (i.e., thickness larger than width) could be formed to provide increased gate control of the transistor channel.

Step (G): FIG. **10G** illustrates the structure after Step (G). A silicon oxide layer **1030** may then be deposited and planarized. The silicon oxide layer is shown transparent in the figure for clarity, along with word-line (WL) **1032** and source-line (SL) **1034** regions.

Step (H): FIG. **10H** illustrates the structure after Step (H). Vias may be etched through multiple layers of silicon and silicon dioxide as shown in the figure. A resistance change memory material **1036** may then be deposited (preferably with atomic layer deposition (ALD)). Examples of such a material include hafnium oxide, well known to change resistance by applying voltage. An electrode for the resistance change memory element may then be deposited (preferably using ALD) and is shown as electrode/BL contact **1040**. A CMP process may then be conducted to planarize the surface. It can be observed that multiple resistance change memory elements in series with junctionless transistors are created after this step.

Step (I): FIG. **10I** illustrates the structure after Step (I). BLs **1038** may then be constructed. Contacts may be made to BLs, WLs and SLs of the memory array at its edges. SL contacts can be made into stair-like structures using techniques described in "Bit Cost Scalable Technology with Punch and Plug Process for Ultra High Density Flash Memory," *VLSI Technology, 2007 IEEE Symposium on*, vol.,

no., pp. 14-15, 12-14 Jun. 2007 by Tanaka, H.; Kido, M.; Yahashi, K.; Oomura, M.; et al., following which contacts can be constructed to them. Formation of stair-like structures for SLs could be achieved in steps prior to Step (I) as well. FIG. 10J shows cross-sectional views of the array for clarity. A 3D resistance change memory has thus been constructed, with (1) horizontally-oriented transistors—i.e. current flowing in substantially the horizontal direction in transistor channels, (2) some of the memory cell control lines, e.g., source-lines SL, constructed of heavily doped silicon and embedded in the memory cell layer, (3) side gates that are simultaneously deposited over multiple memory layers for transistors, and (4) monocrystalline (or single-crystal) silicon layers obtained by layer transfer techniques such as ion-cut.

FIG. 11A-K describe an alternative process flow to construct a horizontally-oriented monolithic 3D resistive memory array. This embodiment has a resistance-based memory element in series with a transistor selector. No mask is utilized on a “per-memory-layer” basis for the monolithic 3D resistance change memory (or resistive memory) concept shown in FIG. 11A-K, and all other masks may be shared between different layers. The process flow may include several steps as described in the following sequence.

Step (A): Peripheral circuits with tungsten wiring **1102** may be first constructed and above this a layer of silicon dioxide **1104** is deposited. FIG. 11A shows a drawing illustration after Step (A).

Step (B): FIG. 11B illustrates the structure after Step (B). A wafer of p-Silicon **1108** may have an oxide layer **1106** grown or deposited above it. Following this, hydrogen may be implanted into the p-Silicon wafer at a certain depth indicated by **1114**. Alternatively, some other atomic species such as Helium could be (co-)implanted. This hydrogen implanted p-Silicon wafer **1108** may form the top layer **1110**. The bottom layer **1112** may include the peripheral circuits **1102** with oxide layer **1104**. The top layer **1110** may be flipped and bonded to the bottom layer **1112** using oxide-to-oxide bonding.

Step (C): FIG. 11C illustrates the structure after Step (C). The stack of top and bottom wafers after Step (B) may be cleaved at the hydrogen plane **1114** using either an anneal or a sideways mechanical force or other means. A CMP process may then be conducted. A layer of silicon oxide **1118** may then be deposited atop the p-Silicon layer **1116**. At the end of this step, a single-crystal p-Silicon layer **1116** exists atop the peripheral circuits, and this has been achieved using layer-transfer techniques.

Step (D): FIG. 11D illustrates the structure after Step (D). Using methods similar to Step (B) and (C), multiple p-silicon layers **1120** may be formed with silicon oxide layers in between. The composition of the silicon oxide regions within the stacked Si/SiO₂ layers may be insulators or dielectrics other than silicon dioxide such as, for example, a low-k dielectric, carbon containing silicon oxides, amorphous carbon. The thickness of silicon oxide regions within the stacked Si/SiO₂ layers may be adjusted to minimize layer to layer, strata to strata disturb mechanisms, and may include thicknesses of 50 nm, 75 nm, 100 nm, 150 nm, 200 nm, 500 nm, and less than 1000 nm. A thin conductive layer, such as a metal, may also be formed between the two bonding oxides to form a field shield to mitigate layer to layer, strata to strata disturb mechanisms, and may be electrically floating or tied to a bias, such as ground or V_{dd}. The stacked Si/SiO₂ layers may alternatively be formed by successive ion implants of oxygen atoms/ions to various depths from the top surface of a mono-crystalline silicon wafer/substrate

and then heat treated to form oxide layers thus forming silicon layers in-between the oxide layers, a layered ‘SIMOX’ process approach.

Step (E): FIG. 11E illustrates the structure after Step (E), including insulator regions such as silicon oxide **1122**. Lithography and etch processes may then be utilized to construct a structure as shown in the figure.

Step (F): FIG. 11F illustrates the structure on after Step (F). Gate dielectric **1126** and gate electrode **1124** may then be deposited following which a CMP may be done to planarize the gate electrode **1124** regions. Lithography and etch may be utilized to define gate regions. Gate dielectric **1126** and gate electrode **1124** may be, for example, a HKMG structure or a TEL SPA radical oxidation oxide and an appropriate work function electrode, for example, tungsten, degenerately doped polysilicon or amorphous silicon. Although the width of the p- regions **1121** near and under the gates are illustrated as being larger than the thickness, one skilled in the art would recognize that the reverse (i.e., thickness larger than width) could be formed to provide increased gate control of the transistor channel.

Step (G): FIG. 11G illustrates the structure after Step (G). Using the hard mask defined in Step (F), p- regions not covered by the gate may be implanted to form n+ regions **1128**. Spacers may be utilized during this multi-step implantation process and layers of silicon present in different layers of the stack may have different spacer widths to account for lateral straggle of buried layer implants. Bottom layers could have larger spacer widths than top layers. A thermal annealing step, such as a RTA or spike anneal or laser anneal or flash anneal, may then be conducted to activate n+ doped regions.

Step (H): FIG. 11H illustrates the structure after Step (H). A silicon oxide layer **1130** may then be deposited and planarized. The silicon oxide layer is shown transparent in the figure for clarity, along with word-line (WL) **1132** and source-line (SL) **1134** regions.

Step (I): FIG. 11I illustrates the structure after Step (I). Vias may be etched through multiple layers of silicon and silicon dioxide as shown in the figure. A resistance change memory material **1136** may then be deposited (preferably with atomic layer deposition (ALD)). Examples of such a material include hafnium oxide, which is well known to change resistance by applying voltage. An electrode for the resistance change memory element may then be deposited (preferably using ALD) and is shown as electrode/BL contact **1140**. A CMP process may then be conducted to planarize the surface. It can be observed that multiple resistance change memory elements in series with transistors are created after this step.

Step (J): FIG. 11J illustrates the structure after Step (J). BLs **1138** may be constructed. Contacts may be made to BLs, WLs and SLs of the memory array at its edges. SL contacts can be made into stair-like structures using techniques described in “Bit Cost Scalable Technology with Punch and Plug Process for Ultra High Density Flash Memory,” *VLSI Technology, 2007 IEEE Symposium on*, vol., no., pp. 14-15, 12-14 Jun. 2007 by Tanaka, H.; Kido, M.; Yahashi, K.; Oomura, M.; et al., following which contacts can be constructed to them. Formation of stair-like structures for SLs could be done in steps prior to Step (I) as well.

FIG. 11K shows cross-sectional views of the array for clarity.

A 3D resistance change memory has thus been constructed, with (1) horizontally-oriented transistors—i.e. current flowing in substantially the horizontal direction in transistor channels, (2) some of the memory cell control lines—e.g.,

source-lines SL, constructed of heavily doped silicon and embedded in the memory cell layer, (3) side gates simultaneously deposited over multiple memory layers for transistors, and (4) monocrystalline (or single-crystal) silicon layers obtained by layer transfer techniques such as ion-cut.

FIG. 12A-L describes an alternative process flow to construct a horizontally-oriented monolithic 3D resistive memory array. This embodiment has a resistance-based memory element in series with a transistor selector. One mask is utilized on a “per-memory-layer” basis for the monolithic 3D resistance change memory (or resistive memory) concept shown in FIG. 12A-L, and all other masks may be shared between different layers. The process flow may include several steps as described in the following sequence.

Step (A): Peripheral circuits **1202** with tungsten wiring may be first constructed and above this a layer of silicon dioxide **1204** may be deposited. FIG. 12A illustrates the structure after Step (A).

Step (B): FIG. 12B illustrates the structure after Step (B). A wafer of p-Silicon **1206** may have an oxide layer **1208** grown or deposited above it. Following this, hydrogen may be implanted into the p-Silicon wafer at a certain depth indicated by **1210**. Alternatively, some other atomic species such as Helium could be (co-)implanted. This hydrogen implanted p-Silicon wafer **1206** may form the top layer **1212**. The bottom layer **1214** may include the peripheral circuits **1202** with oxide layer **1204**. The top layer **1212** may be flipped and bonded to the bottom layer **1214** using oxide-to-oxide bonding.

Step (C): FIG. 12C illustrates the structure after Step (C). The stack of top and bottom wafers after Step (B) may be cleaved at the hydrogen plane **1210** using either an anneal or a sideways mechanical force or other means. A CMP process may be conducted. At the end of this step, a single-crystal p-Si layer exists atop the peripheral circuits, and this has been achieved using layer-transfer techniques.

Step (D): FIG. 12D illustrates the structure after Step (D). Using lithography and then implantation, n+ regions **1216** and p- regions **1218** may be formed on the transferred layer of p-Si after Step (C).

Step (E): FIG. 12E illustrates the structure after Step (E). An oxide layer **1220** may be deposited atop the structure obtained after Step (D). A first layer of Si/SiO₂ **1222** may be formed atop the peripheral circuit layer **1202**. The composition of the ‘SiO₂’ layer within the stacked Si/SiO₂ layers such as Si/SiO₂ **1222**, may be insulators or dielectrics other than silicon dioxide such as, for example, a low-k dielectric, carbon containing silicon oxides, amorphous carbon. The thickness of the ‘SiO₂’ insulator layer within the stacked Si/SiO₂ layers such as Si/SiO₂ **1222** may be adjusted to minimize layer to layer, strata to strata disturb mechanisms, and may include thicknesses of 50 nm, 75 nm, 100 nm, 150 nm, 200 nm, 500 nm, and less than 1000 nm. A thin conductive layer, such as a metal, may also be formed between the two bonding oxides to form a field shield to mitigate layer to layer, strata to strata disturb mechanisms, and may be electrically floating or tied to a bias, such as ground or V_{dd}. The stacked Si/SiO₂ layers, such as Si/SiO₂ **1222**, may alternatively be formed by successive ion implants of oxygen atoms/ions to various depths from the top surface of a mono-crystalline silicon wafer/substrate and then heat treated to form oxide layers thus forming silicon layers in-between the oxide layers, a layered ‘SIMOX’ process approach.

Step (F): FIG. 12F illustrates the structure after Step (F). Using procedures similar to Steps (B)-(E), additional

Si/SiO₂ layers **1224** and **1226** may be formed atop Si/SiO₂ layer **1222**. A rapid thermal anneal (RTA) or spike anneal or flash anneal or laser anneal may be done to activate implanted layers **1222**, **1224** and **1226** (and possibly also the peripheral circuit layer **1202**). Alternatively, the layers **1222**, **1224** and **1226** may be annealed layer-by-layer as soon as their implantations are done using a laser anneal system.

Step (G): FIG. 12G illustrates the structure after Step (G). Lithography and etch processes may be utilized to make a structure as shown in the figure.

Step (H): FIG. 12H illustrates the structure after Step (H). Gate dielectric **1228** and gate electrode **1230** may be deposited following which a CMP may be done to planarize the gate electrode **1230** regions. Lithography and etch may be utilized to define gate regions over the p-silicon regions (eg. p-Si region **1218** after Step (D)). Note that gate width could be slightly larger than p- region width to compensate for overlay errors in lithography. Gate dielectric **1228** and gate electrode **1230** may be, for example, a HKMG structure or a TEL SPA radical oxidation oxide and an appropriate work function electrode, for example, tungsten, degenerately doped polysilicon or amorphous silicon. Although the width of the p- regions **1217** and n+ regions **1215** near and under the gates are illustrated as being larger than the thickness, one skilled in the art would recognize that the reverse (i.e., thickness larger than width) could be formed to provide increased gate control of the transistor channel.

Step (I): FIG. 12I illustrates the structure after Step (I). A silicon oxide layer **1232** may be deposited and planarized. It is shown transparent in the figure for clarity. Word-line (WL) and Source-line (SL) regions are shown in the figure.

Step (J): FIG. 12J illustrates the structure after Step (J). Vias may be etched through multiple layers of silicon and silicon dioxide as shown in the figure. A resistance change memory material **1236** may be deposited (preferably with atomic layer deposition (ALD)). Examples of such a material include hafnium oxide, which is well known to change resistance by applying voltage. An electrode for the resistance change memory element may be deposited (preferably using ALD) and is shown as electrode/BL contact **1240**. A CMP process may be conducted to planarize the surface. It can be observed that multiple resistance change memory elements in series with transistors are created after this step. Step (K): FIG. 12K illustrates the structure after Step (K). BLs **1236** may be constructed. Contacts may be made to BLs **1238**, WLs **1232** and SLs **1234** of the memory array at its edges. SL contacts can be made into stair-like structures using techniques described in “Bit Cost Scalable Technology with Punch and Plug Process for Ultra High Density Flash Memory,” *VLSI Technology*, 2007 *IEEE Symposium on*, vol., no., pp. 14-15, 12-14 Jun. 2007 by Tanaka, H.; Kido, M.; Yahashi, K.; Oomura, M.; et al., following which contacts can be constructed to them. Formation of stair-like structures for SLs could be achieved in steps prior to Step (J) as well.

FIG. 12L shows cross-sectional views of the array for clarity.

A 3D resistance change memory has thus been constructed, with (1) horizontally-oriented transistors—i.e. current flowing in substantially the horizontal direction in transistor channels, (2) some of the memory cell control lines, e.g., source-lines SL, constructed of heavily doped silicon and embedded in the memory cell layer, (3) side gates simultaneously deposited over multiple memory layers for transistors, and (4) monocrystalline (or single-crystal) silicon layers obtained by layer transfer techniques such as ion-cut.

FIG. 13A-F describes an alternative process flow to construct a horizontally-oriented monolithic 3D resistive memory array. This embodiment has a resistance-based memory element in series with a transistor selector. Two masks are utilized on a “per-memory-layer” basis for the monolithic 3D resistance change memory (or resistive memory) concept shown in FIG. 13A-F, and all other masks may be shared between different layers. The process flow may include several steps as described in the following sequence.

Step (A): The process flow may start with a p-silicon wafer **1302** with an oxide coating **1304**. FIG. 13A illustrates the structure after Step (A).

Step (B): FIG. 13B illustrates the structure after Step (B). Using a process flow similar to FIG. 12B, a portion of the p-silicon layer **1302** may be transferred atop a layer of peripheral circuits **1306**. The peripheral circuits **1306** preferably use tungsten wiring.

Step (C): FIG. 13C illustrates the structure after Step (C). Isolation regions for transistors may be formed using a shallow-trench-isolation (STI) process. Following this, a gate dielectric **1310** and a gate electrode **1308** may be deposited. Gate dielectric **1310** and gate electrode **1308** may be, for example, a HKMG structure or a TEL SPA radical oxidation oxide and an appropriate work function electrode, for example, tungsten, degenerately doped polysilicon or amorphous silicon.

Step (D): FIG. 13D illustrates the structure after Step (D). The gate may be patterned, and source-drain regions **1312** may be formed by implantation. An inter-layer dielectric (ILD) **1314** may be also formed.

Step (E): FIG. 13E illustrates the structure after Step (E). Using steps similar to Step (A) to Step (D), a second layer of transistors **1316** may be formed above the first layer of transistors **1314**. An RTA or some other type of anneal, such as the optical anneals described herein, may be performed to activate dopants in the memory layers (and potentially also the peripheral transistors).

Step (F): FIG. 13F illustrates the structure after Step (F). Vias may be etched through multiple layers of silicon and silicon dioxide as shown in the figure. A resistance change memory material **1322** may be deposited (preferably with atomic layer deposition (ALD)). Examples of such a material include hafnium oxide, which is well known to change resistance by applying voltage. An electrode for the resistance change memory element may be deposited (preferably using ALD) and is shown as electrode **1326**. A CMP process may be conducted to planarize the surface. Contacts are made to drain terminals of transistors in different memory layer as well. Note that gates of transistors in each memory layer may be connected together perpendicular to the plane of the figure to form word-lines (WL **1320**). Wiring for bit-lines (BL **1318**) and source-lines (SL **1324**) may be constructed. Contacts may be made between BLs, WLs and SLs with the periphery at edges of the memory array. Multiple resistance change memory elements in series with transistors may be created after this step.

A 3D resistance change memory has thus been constructed, with (1) horizontally-oriented transistors—i.e. current flowing in substantially the horizontal direction in the transistor channels, and (2) monocrystalline (or single-crystal) silicon layers obtained by layer transfer techniques such as ion-cut.

While explanations have been given for formation of monolithic 3D resistive memories with ion-cut in this section, it is clear to one skilled in the art that alternative implementations are possible. BL and SL nomenclature has been used for two terminals of the 3D resistive memory

array, and this nomenclature can be interchanged. Moreover, selective epi technology or laser recrystallization technology could be utilized for implementing structures shown in FIG. 10A-J, FIG. 11A-K, FIG. 12A-L and FIG. 13A-F. Various other types of layer transfer schemes that have been described herein and in incorporated patent references can be utilized for construction of various 3D resistive memory structures. One could also use buried wiring, i.e. where wiring for memory arrays is below the memory layers but above the periphery. Other variations of the monolithic 3D resistive memory concepts are possible.

Section 3: Monolithic 3D Charge-Trap Memory

While resistive memories described previously form a class of non-volatile memory, others classes of non-volatile memory exist. NAND flash memory forms one of the most common non-volatile memory types. It can be constructed of two main types of devices: floating-gate devices where charge is stored in a floating gate and charge-trap devices where charge is stored in a charge-trap layer such as Silicon Nitride. Background information on charge-trap memory can be found in “*Integrated Interconnect Technologies for 3D Nanoelectronic Systems*”, Artech House, 2009 by Bakir and Meindl (“Bakir”) and “A Highly Scalable 8-Layer 3D Vertical-Gate (VG) TFT NAND Flash Using Junction-Free Buried Channel BE-SONOS Device,” Symposium on VLSI Technology, 2010 by Hang-Ting Lue, et al. The architectures shown in FIG. 14A-F, FIG. 15A-G and FIG. 16A-D are relevant for any type of charge-trap memory.

FIG. 14A-F describes a process flow to construct a horizontally-oriented monolithic 3D charge trap memory. Two masks are utilized on a “per-memory-layer” basis for the monolithic 3D charge trap memory concept shown in FIG. 14A-F, while other masks may be shared between all constructed memory layers. The process flow may include several steps, which may occur in the following sequence. Step (A): A p-Silicon wafer **1402** may be taken and an oxide layer **1404** may be grown or deposited above it. FIG. 14A illustrates the structure after Step (A).

Step (B): FIG. 14B illustrates the structure after Step (B). Using a procedure similar to the one shown in FIG. 12B, a portion of the p-Si wafer **1402**, such as p-silicon layer **1403**, may be transferred atop a peripheral circuit layer **1406**. The periphery may be designed such that it can withstand the RTA or optical anneals for activating dopants in the memory layers formed atop it.

Step (C): FIG. 14C illustrates the structure after Step (C). Isolation regions may be formed in the p-Si layer **1403** atop the peripheral circuit layer **1406**. This lithography step and all future lithography steps may be formed with good alignment to features on the peripheral circuit layer **1406** since the p-silicon layer **1403** is thin and reasonably transparent to the lithography tool. A dielectric layer **1410** (eg. Oxide-nitride-oxide ONO layer) may be deposited following which a gate electrode layer **1408** (eg. polysilicon) may be deposited.

Step (D): FIG. 14D illustrates the structure after Step (D). The gate regions deposited in Step (C) may be patterned and etched. Following this, source-drain regions **1412** may be implanted. An inter-layer dielectric **1414** may be deposited and planarized.

Step (E): FIG. 14E illustrates the structure after Step (E). Using procedures similar to Step (A) to Step (D), another layer of memory, such as a second NAND string **1416**, may be formed atop the first NAND string **1414**.

Step (F): FIG. 14F illustrates the structure after Step (F). Contacts **1418** may be made to connect bit-lines (BL) and source-lines (SL) to the NAND string. Contacts to the well

of the NAND string may be made. All these contacts could be constructed of heavily doped polysilicon or some other material. An anneal to activate dopants in source-drain regions of transistors in the NAND string (and potentially also the periphery) may be conducted. Following this, construction of wiring layers for the memory array may be conducted.

A 3D charge-trap memory has thus been constructed, with (1) horizontally-oriented transistors—i.e. current flowing in substantially the horizontal direction in transistor channels, and (2) monocrystalline (or single-crystal) silicon layers obtained by layer transfer techniques such as ion-cut. This use of monocrystalline silicon (or single crystal silicon) using ion-cut can be a key differentiator for some embodiments of the current invention vis-à-vis prior work.

FIG. 15A-G describes a memory architecture for single-crystal 3D charge-trap memories, and a procedure for its construction. It utilizes junction-less transistors. No mask is utilized on a “per-memory-layer” basis for the monolithic 3D charge-trap memory concept shown in FIG. 15A-G, and all other masks are shared between different layers. The process flow may include several steps as described in the following sequence.

Step (A): Peripheral circuits **1502** may be constructed and above this a layer of silicon dioxide **1504** may be deposited. FIG. 15A shows a drawing illustration after Step (A).

Step (B): FIG. 15B illustrates the structure after Step (B). A wafer of n+Silicon **1508** may have an oxide layer **1506** grown or deposited above it. Following this, hydrogen may be implanted into the n+Silicon wafer at a certain depth indicated by **1514**. Alternatively, some other atomic species such as Helium could be implanted. This hydrogen implanted n+Silicon wafer **1508** may form the top layer **1510**. The bottom layer **1512** may include the peripheral circuits **1502** with oxide layer **1504**. The top layer **1510** may be flipped and bonded to the bottom layer **1512** using oxide-to-oxide bonding.

Step (C): FIG. 15C illustrates the structure after Step (C). The stack of top and bottom wafers after Step (B) may be cleaved at the hydrogen plane **1514** using either an anneal or a sideways mechanical force or other means. A CMP process may be conducted. A layer of silicon oxide **1518** may be deposited atop the n+Silicon layer **1516**. At the end of this step, a single-crystal n+Si layer **1516** exists atop the peripheral circuits, and this has been achieved using layer-transfer techniques.

Step (D): FIG. 15D illustrates the structure after Step (D). Using methods similar to Step (B) and (C), multiple n+ silicon layers **1520** may be formed with silicon oxide layers in between. The composition of the ‘SiO₂’ layer within the stacked Si/SiO₂ layers may be insulators or dielectrics other than silicon dioxide such as, for example, a low-k dielectric, carbon containing silicon oxides, amorphous carbon. The thickness of the ‘SiO₂’ insulator layer within the stacked Si/SiO₂ layers may be adjusted to minimize layer to layer, strata to strata disturb mechanisms, and may include thicknesses of 50 nm, 75 nm, 100 nm, 150 nm, 200 nm, 500 nm, and less than 1000 nm. A thin conductive layer, such as a metal, may also be formed between the two bonding oxides to form a field shield to mitigate layer to layer, strata to strata disturb mechanisms, and may be electrically floating or tied to a bias, such as ground or V_{dd}. The stacked Si/SiO₂ layers may alternatively be formed by successive ion implants of oxygen atoms/ions to various depths from the top surface of a mono-crystalline silicon wafer/substrate and then heat

treated to form oxide layers thus forming silicon layers in-between the oxide layers, a layered ‘SIMOX’ process approach.

Step (E): FIG. 15E illustrates the structure after Step (E). Lithography and etch processes may be utilized to make a structure as shown in the figure.

Step (F): FIG. 15F illustrates the structure after Step (F). Gate dielectric **1526** and gate electrode **1524** may be deposited following which a CMP may be done to planarize the gate electrode **1524** regions. Lithography and etch may be utilized to define gate regions. Gates of the NAND string **1536** as well as gates of select gates of the NAND string **1538** may be defined. Gate dielectric **1526** and gate electrode **1524** may be, for example, a HKMG structure or a TEL SPA radical oxidation oxide and an appropriate work function electrode, for example, tungsten, degenerately doped polysilicon or amorphous silicon. Although the width of the n+ regions near and under the gates are illustrated as being larger than the thickness, one skilled in the art would recognize that the reverse (i.e., thickness larger than width) could be formed to provide increased gate control of the transistor channel.

Step (G): FIG. 15G illustrates the structure after Step (G). A silicon oxide layer **1530** may be deposited and planarized. It is shown transparent in the figure for clarity. Word-lines, bit-lines and source-lines may be defined as shown in the figure, including wiring for the select gates **1532** and cell source regions **1534** for connection to the cell sources. Contacts may be formed to various regions/wires at the edges of the array as well. SL contacts can be made into stair-like structures using techniques described in “Bit Cost Scalable Technology with Punch and Plug Process for Ultra High Density Flash Memory,” *VLSI Technology, 2007 IEEE Symposium on*, vol., no., pp. 14-15, 12-14 Jun. 2007 by Tanaka, H.; Kido, M.; Yahashi, K.; Oomura, M.; et al., following which contacts can be constructed to them. Formation of stair-like structures for SLs could be performed in steps prior to Step (G) as well.

A 3D charge-trap memory has thus been constructed, with (1) horizontally-oriented transistors—i.e. current flowing in substantially the horizontal direction in transistor channels, (2) some of the memory cell control lines—e.g., bit lines BL, constructed of heavily doped silicon and embedded in the memory cell layer, (3) side gates simultaneously deposited over multiple memory layers for transistors, and (4) monocrystalline (or single-crystal) silicon layers obtained by layer transfer techniques such as ion-cut. This use of single-crystal silicon obtained with ion-cut is a key differentiator from past work on 3D charge-trap memories such as “A Highly Scalable 8-Layer 3D Vertical-Gate (VG) TFT NAND Flash Using Junction-Free Buried Channel BE-SONOS Device,” *Symposium on VLSI Technology, 2010* by Hang-Ting Lue, et al. that used polysilicon.

While FIG. 14A-F and FIG. 15A-G give two examples of how single-crystal silicon layers with ion-cut can be used to produce 3D charge-trap memories, the ion-cut technique for 3D charge-trap memory is fairly general. It could be utilized to produce any horizontally-oriented 3D monocrystalline-silicon charge-trap memory. FIG. 16A-D further illustrate how general the process can be. One or more doped silicon layers **1602** can be layer transferred atop any peripheral circuit layer **1606** using procedures shown in FIG. 12B, including insulator layers such as oxide **1604**. These are indicated in FIG. 16A, FIG. 16B and FIG. 16C. Following this, different procedures can be utilized to form different types of 3D charge-trap memories. For example, procedures shown in “A Highly Scalable 8-Layer 3D Vertical-Gate

(VG) TFT NAND Flash Using Junction-Free Buried Channel BE-SONOS Device,” Symposium on VLSI Technology, 2010 by Hang-Ting Lue, et al. and “Multi-layered Vertical Gate NAND Flash overcoming stacking limit for terabit density storage”, Symposium on VLSI Technology, 2009 by W. Kim, S. Choi, et al. can be used to produce the two different types of horizontally oriented single crystal silicon 3D charge trap memory shown in FIG. 16D.

Section 4: Monolithic 3D Floating-Gate Memory

While charge-trap memory forms one type of non-volatile memory, floating-gate memory is another type. Background information on floating-gate NAND flash memory can be found in Bez, R. et al. Introduction to Flash memory. Proc. IEEE 91, 489-502 (2003). There are different types of floating-gate memory based on different materials and device structures. The architectures shown in FIG. 17A-F and FIG. 18A-H are relevant for any type of floating-gate memory.

FIG. 17A-F describe a process flow to construct a horizontally-oriented monolithic 3D floating-gate memory. Two masks are utilized on a “per-memory-layer” basis for the monolithic 3D floating-gate memory concept shown in FIG. 17A-F, while other masks may be shared between all constructed memory layers. The process flow may include several steps as described in the following sequence.

Step (A): A p-Silicon wafer 1702 may be taken and an oxide layer 1704 may be grown or deposited above it. FIG. 17A illustrates the structure after Step (A).

Step (B): FIG. 17B illustrates the structure after Step (B). Using a procedure similar to the one shown in FIG. 12B, a portion of the p-Si wafer 1702, such as p-silicon layer 1703, may be transferred atop a peripheral circuit layer 1706. The periphery may be designed such that it can withstand the RTA or optical annealing techniques for activating dopants in memory layers formed atop it.

Step (C): FIG. 17C illustrates the structure after Step (C). After deposition of the tunnel oxide 1710 and floating gate 1708, isolation regions may be formed in the p-silicon layer 1703 atop the peripheral circuit layer 1706. This lithography step and all future lithography steps may be formed with good alignment to features on the peripheral circuit layer 1706 since the p-silicon layer 1703 is thin and reasonably transparent to the lithography tool.

Step (D): FIG. 17D illustrates the structure after Step (D). An inter-poly-dielectric (IPD) layer (eg. Oxide-nitride-oxide ONO layer) may be deposited following which a control gate electrode 1720 (eg. polysilicon) may be deposited. The gate regions deposited in Step (C) may be patterned and etched. Following this, source-drain regions 1712 may be implanted. An inter-layer dielectric 1714 may be deposited and planarized.

Step (E): FIG. 17E illustrates the structure after Step (E). Using procedures similar to Step (A) to Step (D), another layer of memory, a second NAND string 1716, may be formed atop the first NAND string 1714.

Step (F): FIG. 17F illustrates the structure after Step (F). Contacts 1718 may be made to connect bit-lines (BL) and source-lines (SL) to the NAND string. Contacts to the well of the NAND string may be made. All these contacts could be constructed of heavily doped polysilicon or some other material. An anneal to activate dopants in source-drain regions of transistors in the NAND string (and potentially also the periphery) may be conducted. Following this, wiring layers for the memory array may be constructed.

A 3D floating-gate memory has thus been constructed, with (1) horizontally-oriented transistors—i.e. current flow in substantially the horizontal direction in transistor channels,

(2) monocrystalline (or single-crystal) silicon layers obtained by layer transfer techniques such as ion-cut. This use of monocrystalline silicon (or single crystal silicon) using ion-cut is a key differentiator for some embodiments of the current invention vis-à-vis prior work. Past work used selective epi technology or laser recrystallization or polysilicon.

FIG. 18A-H show a novel memory architecture for 3D floating-gate memories, and a procedure for its construction. The memory architecture utilizes junction-less transistors. One mask is utilized on a “per-memory-layer” basis for the monolithic 3D floating-gate memory concept shown in FIG. 18A-H, and all other masks may be shared between different layers. The process flow may include several steps that may be described in the following sequence.

Step (A): Peripheral circuits 1802 may be constructed and above this a layer of silicon dioxide 1804 may be deposited. FIG. 18A illustrates the structure after Step (A).

Step (B): FIG. 18B illustrates the structure after Step (B). A wafer of n+Silicon 1808 may have an oxide layer 1806 grown or deposited above it. Following this, hydrogen may be implanted into the n+Silicon wafer at a certain depth indicated by 1814. Alternatively, some other atomic species such as Helium could be implanted. This hydrogen implanted n+Silicon wafer 1808 may form the top layer 1810. The bottom layer 1812 may include the peripheral circuits 1802 with oxide layer 1804. The top layer 1810 may be flipped and bonded to the bottom layer 1812 using oxide-to-oxide bonding.

Step (C): FIG. 18C illustrates the structure after Step (C). The stack of top and bottom wafers after Step (B) may be cleaved at the hydrogen plane 1814 using either an anneal or a sideways mechanical force or other means. A CMP process may be conducted. At the end of this step, a single-crystal n+Si layer 1816 exists atop the peripheral circuits, and this has been achieved using layer-transfer techniques.

Step (D): FIG. 18D illustrates the structure after Step (D). Using lithography and etch, the n+ silicon layer 1807 may be defined.

Step (E): FIG. 18E illustrates the structure after Step (E). A tunnel oxide layer 1808 may be grown or deposited following which a polysilicon layer 1810 for forming future floating gates may be deposited. A CMP process may be conducted.

Step (F): FIG. 18F illustrates the structure after Step (F). Using similar procedures, multiple levels of memory may be formed with oxide layers in between.

Step (G): FIG. 18G illustrates the structure after Step (G). The polysilicon region for floating gates 1810 may be etched to form the polysilicon region 1811.

Step (H): FIG. 18H illustrates the structure after Step (H). Inter-poly dielectrics (IPD) 1812 and control gates 1814 may be deposited and polished.

While the steps shown in FIG. 18A-H describe formation of a few floating gate transistors, it will be obvious to one skilled in the art that an array of floating-gate transistors can be constructed using similar techniques and well-known memory access/decoding schemes.

A 3D floating-gate memory has thus been constructed, with (1) horizontally-oriented transistors—i.e. current flowing in substantially the horizontal direction in transistor channels, (2) monocrystalline (or single-crystal) silicon layers obtained by layer transfer techniques such as ion-cut, (3) side gates that are simultaneously deposited over multiple memory layers for transistors, and (4) some of the memory cell control lines are in the same memory layer as the devices. The use of monocrystalline silicon (or single crystal

silicon) layer obtained by ion-cut in (2) is a key differentiator for some embodiments of the current invention vis-à-vis prior work. Past work used selective epi technology or laser recrystallization or polysilicon.

Section 5: Alternative Implementations of Various Monolithic 3D Memory Concepts

While the 3D DRAM and 3D resistive memory implementations in Section 1 and Section 2 have been described with single crystal silicon constructed with ion-cut technology, other options exist. One could construct them with selective epi technology. Procedures for doing these will be clear to those skilled in the art.

Various layer transfer schemes described herein and in patent reference incorporated can be utilized for constructing single-crystal silicon layers for memory architectures described in Section 1, Section 2, Section 3 and Section 4.

FIG. 19A-B show it is not the only option for the architecture, as depicted in FIG. 2-FIG. 18A-H, to have the peripheral transistors, such as within bottom side periphery 1902, below the memory layers, such as memory layer 1 1904, memory layer 2 1906, and memory layer 3 1908. Peripheral transistors, such as within top side periphery 1910, could also be constructed above the memory layers, as shown in FIG. 19B, and may include substrate or memory layer 4 1912. This periphery layer would utilize technologies described in Section 1 and Section 2, and could utilize junction-less transistors or recessed channel transistors, and may utilize optical annealing, shielding layers, and absorbers/reflectors as described in incorporated patent references.

The double gate devices shown in FIG. 2-FIG. 18A-H may have both gates connected to each other. Each gate terminal may be designed to be controlled independently, which may lead to design advantages for memory chips.

One of the concerns with using n+Silicon as a control line for 3D memory arrays is its high resistance. Using lithography and (single-step of multi-step) ion-implantation, one could dope heavily the n+ silicon control lines while not doping transistor gates, sources and drains in the 3D memory array. This preferential doping may mitigate the concern of high resistance.

In many of the described 3D memory approaches, etching and filling high aspect ratio vias forms a serious limitation. One way to circumvent this obstacle is by etching and filling vias from two sides of a wafer. A procedure for doing this is shown in FIG. 20A-E. Although FIG. 20A-E describe the process flow for a resistive memory implementation, similar processes can be used for DRAM, charge-trap memories and floating-gate memories as well. The process may include several steps that proceed in the following sequence:

Step (A): 3D resistive memories may be constructed as shown in FIG. 11A-K but with a bare silicon wafer 2002 instead of a wafer with peripheral circuits on it. Due to aspect ratio limitations, the resistance change memory and BL contact 2036 may be formed to the top layers of the memory, as illustrated in FIG. 20A. Bit line contacts may be formed, for example, as sidewall structures or end-wall structures, with various overlaps as required by the process and layout.

Step (B): Hydrogen may be implanted into the wafer 2002 at a certain depth such as hydrogen implant plane 2042. FIG. 20B illustrates the structure after Step B including silicon oxide 2022.

Step (C): The wafer with the structure after Step (B) may be bonded to a bare silicon wafer 2044. Cleaving may be performed at the hydrogen implant plane 2042. A CMP process may be conducted to polish off the silicon wafer. FIG. 20C illustrates the structure after Step C.

Step (D): Resistance change memory material and BL contact layers 2041 may be constructed for the bottom memory layers. They may connect to the partially made top BL contacts 2036 with state-of-the-art alignment. Bit line contacts may be formed, for example, as sidewall structures or end-wall structures, with various overlaps as required by the process and layout. FIG. 20D illustrates the structure after Step D, including gate electrodes 2024, gate dielectric 2026, n+ silicon regions 2028, BL contacts 2040, BLs 3038, WLs 2032, and SL 2034.

Step (E): Peripheral transistors 2046 may be constructed using procedures shown previously in this document. FIG. 20E illustrates the structure after Step E. Connections may be made to various wiring layers.

The charge-trap and floating-gate architectures shown in FIG. 14A-F-FIG. 18A-H are based on NAND flash memory. To one skilled in the art that these architectures can be modified into a NOR flash memory style as well.

Section 6: Poly-Silicon-Based Implementation of Various Memory Concepts

The monolithic 3D integration concepts described herein can lead to novel embodiments of poly-silicon-based memory architectures as well. Poly silicon based architectures could potentially be cheaper than single crystal silicon based architectures when a large number of memory layers need to be constructed. While the below concepts are explained by using resistive memory architectures as an example, it will be clear to one skilled in the art that similar concepts can be applied to NAND flash memory and DRAM architectures described previously in this patent application.

FIG. 21A-E shows an embodiment of the current invention, where polysilicon junctionless transistors are used to form a 3D resistance-based memory. The utilized junctionless transistors can have either positive or negative threshold voltages. The process may include the following steps as described in the following sequence:

Step (A): As illustrated in FIG. 21A, peripheral circuits 2102 may be constructed above which a layer of silicon dioxide 2104 may be made.

Step (B): As illustrated in FIG. 21B, multiple layers of n-doped amorphous silicon or polysilicon 2106 may be deposited with layers of silicon dioxide 2108 in between. The amorphous silicon or polysilicon layers 2106 could be deposited using a chemical vapor deposition process, such as LPCVD or PECVD. The composition of the 'SiO₂' layer within the stacked Si/SiO₂ layers such as silicon dioxide 2108, may be insulators or dielectrics other than silicon dioxide such as, for example, a low-k dielectric, carbon containing silicon oxides, amorphous carbon. The thickness of the 'SiO₂' insulator layer within the stacked Si/SiO₂ layers such as silicon dioxide 2108 may be adjusted to minimize layer to layer, strata to strata disturb mechanisms, and may include thicknesses of 50 nm, 75 nm, 100 nm, 150 nm, 200 nm, 500 nm, and less than 1000 nm. A thin conductive layer, such as a metal, may also be formed between the two bonding oxides to form a field shield to mitigate layer to layer, strata to strata disturb mechanisms, and may be electrically floating or tied to a bias, such as ground or Vdd. The stacked Si/SiO₂ layers may alternatively be formed by successive ion implants of oxygen atoms/ions to various depths from the top surface of a mono-crystalline silicon wafer/substrate and then heat treated to form oxide layers thus forming silicon layers in-between the oxide layers, a layered SIMOX' process approach.

Step (C): As illustrated in FIG. 21C, a Rapid Thermal Anneal (RTA) may be conducted to crystallize the layers of polysilicon or amorphous silicon deposited in Step (B).

Temperatures during this RTA could be as high as 210° C. or more, and could even be as high as 800° C. The polysilicon region obtained after Step (C) is indicated as 2110. Alternatively, a laser anneal could be conducted, either for all layers 2106 at the same time or layer by layer.

Step (D): As illustrated in FIG. 21D, procedures similar to those described in FIG. 10E-H may be utilized to construct the structure shown. The structure in FIG. 21D has multiple levels of junction-less transistor selectors for resistive memory devices, including isolation regions such as silicon oxide regions 2130. The resistance change memory is indicated as 2136 while its electrode and contact to the BL is indicated as 2140. The WL is indicated as 2132, while the SL is indicated as 2134. Gate dielectric of the junction-less transistor is indicated as 2126 while the gate electrode of the junction-less transistor is indicated as 2124, this gate electrode also serves as part of the WL 2132. Gate dielectric 2126 and gate electrode 2124 may be, for example, a HKMG structure or a TEL SPA radical oxidation oxide and an appropriate work function electrode, for example, tungsten, degenerately doped polysilicon or amorphous silicon. Although the width of the n+ regions 2110 near and under the gates are illustrated as being larger than the thickness, one skilled in the art would recognize that the reverse (i.e., thickness larger than width) could be formed to provide increased gate control of the transistor channel.

Step (E): As illustrated in FIG. 21E, bit lines (indicated as BL 2138) may be constructed. Contacts may be made to peripheral circuits and various parts of the memory array as described in embodiments described previously.

FIG. 22A-F show another embodiment of the current invention, where polysilicon junction-less transistors are used to form a 3D resistance-based memory. The utilized junction-less transistors can have either positive or negative threshold voltages. The process may include the following steps:

Step (A): As illustrated in FIG. 22A, a layer of silicon dioxide 2204 may be deposited or grown above a silicon substrate without circuits 2202.

Step (B): As illustrated in FIG. 22B, multiple layers of n+ doped amorphous silicon or polysilicon 2206 may be deposited with layers of silicon dioxide 2208 in between. The amorphous silicon or polysilicon layers 2206 could be deposited using a chemical vapor deposition process, such as LPCVD or PECVD described above. The composition of the 'SiO₂' layer within the stacked Si/SiO₂ layers such as silicon dioxide 2208, may be insulators or dielectrics other than silicon dioxide such as, for example, a low-k dielectric, carbon containing silicon oxides, amorphous carbon. The thickness of the 'SiO₂' insulator layer within the stacked Si/SiO₂ layers such as silicon dioxide 2208 may be adjusted to minimize layer to layer, strata to strata disturb mechanisms, and may include thicknesses of 50 nm, 75 nm, 100 nm, 150 nm, 200 nm, 500 nm, and less than 1000 nm. A thin conductive layer, such as a metal, may also be formed between the two bonding oxides to form a field shield to mitigate layer to layer, strata to strata disturb mechanisms, and may be electrically floating or tied to a bias, such as ground or Vdd. The stacked Si/SiO₂ layers may alternatively be formed by successive ion implants of oxygen atoms/ions to various depths from the top surface of a mono-crystalline silicon wafer/substrate and then heat treated to form oxide layers thus forming silicon layers in-between the oxide layers, a layered 'SIMOX' process approach.

Step (C): As illustrated in FIG. 22C, a Rapid Thermal Anneal (RTA) or standard anneal may be conducted to crystallize the layers of polysilicon or amorphous silicon

deposited in Step (B). Temperatures during this RTA could be as high as 700° C. or more, and could even be as high as 1400° C. The polysilicon region obtained after Step (C) is indicated as 2210. Since there are no circuits under these layers of polysilicon, very high temperatures (such as 1400° C.) can be used for the anneal process, leading to very good quality polysilicon with few grain boundaries and very high mobilities approaching those of single crystal silicon. Alternatively, a laser anneal could be conducted, either for all layers 2206 at the same time or layer by layer at different times.

Step (D): This is illustrated in FIG. 22D. Procedures similar to those described in FIG. 10E-H may be utilized to get the structure shown in FIG. 22D that has multiple levels of junction-less transistor selectors for resistive memory devices, including insulator regions such as silicon oxide regions 2230. The resistance change memory is indicated as 2236 while its electrode and contact to the BL is indicated as 2240. The WL is indicated as 2232, while the SL is indicated as 2234. Gate dielectric of the junction-less transistor is indicated as 2226 while the gate electrode of the junction-less transistor is indicated as 2224, this gate electrode also serves as part of the WL 2232. Gate dielectric 2226 and gate electrode 2224 may be, for example, a HKMG structure or a TEL SPA radical oxidation oxide and an appropriate work function electrode, for example, tungsten, degenerately doped polysilicon or amorphous silicon. Although the width of the n+ regions 2210 near and under the gates are illustrated as being larger than the thickness, one skilled in the art would recognize that the reverse (i.e., thickness larger than width) could be formed to provide increased gate control of the transistor channel.

Step (E): This is illustrated in FIG. 22E. Bit lines (indicated as BL 2238) may be constructed. Contacts may be made to peripheral circuits and various parts of the memory array as described in embodiments described previously.

Step (F): Using procedures described herein and in incorporated by reference patents, peripheral circuits 2298 (with transistors and wires) could be formed well aligned to the multiple memory layers shown in Step (E). For the periphery, one could use the process flow wherein replacement gate processing is used, or one could use sub-400° C. processed transistors such as junction-less transistors or recessed channel transistors. Alternatively, one could use laser anneals for peripheral transistors' source-drain processing. Connections can then be formed between the multiple memory layers and peripheral circuits. By proper choice of materials for memory layer transistors and memory layer wires (e.g., by using tungsten and other materials that withstand high temperature processing for wiring), or by using optical annealing and proper shielding layers, even standard transistors processed at high temperatures (>1000° C.) for the periphery could be used.

Section 7: Monolithic 3D SRAM

The techniques described in this patent application can be used for constructing monolithic 3D SRAMs.

FIG. 23A-D represents an SRAM embodiment of the current invention, wherein ion-cut is utilized for constructing a monolithic 3D SRAM. Peripheral circuits may be constructed on a silicon substrate, and above this, two layers of nMOS transistors and one layer of pMOS transistors may be formed using ion-cut and procedures described earlier in this patent application. Implants for each of these layers may be performed when the layers are being constructed, and finally, after all layers have been constructed, a RTA may be

conducted to activate dopants. If high k dielectrics are utilized for this process, a gate-first approach may be preferred.

FIG. 23A shows a standard six-transistor SRAM cell according to an embodiment of the current invention. There are two pull-down nMOS transistors, and **2302** represents a pull-down nMOS transistor in FIG. 23A-D. There are also two pull-up pMOS transistors, each of which is represented by **2316**. There are two nMOS pass transistors **2304** connecting bit-line wiring **2312** and bit line complement wiring **2314** to the pull-up transistors **2316** and pull-down transistors **2302**, and these are represented by **2314**. Gates of nMOS pass transistors **2314** are represented by **2306** and are connected to word-lines (WL) using WL contacts **2308**. Supply voltage VDD is denoted as **2322** while ground voltage GND is denoted as **2324**. Nodes n1 and n2 within the SRAM cell are represented as **2310**.

FIG. 23B shows a top view of the SRAM according to an embodiment of the invention. For the SRAM described in FIG. 23A-D, the bottom layer may be the periphery. The nMOS pull-down transistors may be above the bottom layer. The pMOS pull-up transistors may be above the nMOS pull-down transistors. The nMOS pass transistors may be above the pMOS pull-up transistors. The nMOS pass transistors **2304** on the topmost layer may be displayed in FIG. 23B. Gates **2306** for nMOS pass transistors **2304** are also shown in FIG. 23B. Other numerals have been described previously in respect of FIG. 23A.

FIG. 23C shows a cross-sectional view of the SRAM according to an embodiment of the invention. Oxide isolation using a STI process is indicated as **2300**. Gates for pull-up pMOS transistors are indicated as **2318** while the vertical contact to the gate of the pull-up pMOS and nMOS transistors is indicated as **2320**. The periphery layer is indicated as **2398**. Other numerals have been described in respect of FIG. 23A and FIG. 23B.

FIG. 23D shows another cross-sectional view of the SRAM according to an embodiment of the current invention. The nodes n1 and n2 may be connected to pull-up, pull-down and pass transistors by using a vertical via **2310**. **2326** is a heavily doped n+Si region of the pull-down transistor, **2328** is a heavily doped p+Si region of the pull-up transistor and **2330** is a heavily doped n+ region of a pass transistor. Other symbols have been described previously in respect of FIG. 23A, FIG. 23B and FIG. 23C. Wiring may connect together different elements of the SRAM as shown in FIG. 23A.

It can be seen that the SRAM cell shown in FIG. 23A-D is small in terms of footprint compared to a standard 6 transistor SRAM cell. Previous work has suggested building six-transistor SRAMs with nMOS and pMOS devices on different layers with layouts similar to the ones described in FIG. 23A-D. These are described in "The revolutionary and truly 3-dimensional 25F² SRAM technology with the smallest S³ (stacked single-crystal Si) cell, 0.16 μm^2 , and SSTFT (stacked single-crystal thin film transistor) for ultra high density SRAM," VLSI Technology, 2004. Digest of Technical Papers. 2004 Symposium on, vol., no., pp. 228-229, 15-17 Jun. 2004 by Soon-Moon Jung; Jaehoon Jang; Wonseok Cho; Jaehwan Moon; Kunho Kwak; Bonghyun Choi; Byungjun Hwang; Hoon Lim; Jaehun Jeong; Jonghyuk Kim; Kinam Kim. However, these devices are constructed using selective epi technology, which suffers from defect issues. These defects severely impact SRAM operation. The embodiment of this invention described in FIG. 23A-D is constructed with ion-cut technology and is thus far less prone to defect issues compared to selective epi technology.

It is clear to one skilled in the art that other techniques described in this patent application, such as use of junctionless transistors or recessed channel transistors, could be utilized to form the structures shown in FIG. 23A-D. Alternative layouts for 3D stacked SRAM cells are possible as well, where heavily doped silicon regions could be utilized as GND, VDD, bit line wiring and bit line complement wiring. For example, the region **2326** (in FIG. 23D), instead of serving just as a source or drain of the pull-down transistor, could also run all along the length of the memory array and serve as a GND wiring line. Similarly, the heavily doped p+Si region **2328** (in FIG. 23D), instead of serving just as a source or drain of the pull-up transistor, could run all along the length of the memory array and serve as a VDD wiring line. The heavily doped n+ region **2330** could run all along the length of the memory array and serve as a bit line.

It will also be appreciated by persons of ordinary skill in the art that the invention is not limited to what has been particularly shown and described hereinabove. For example, drawings or illustrations may not show n or p wells for clarity in illustration. Moreover, transistor channels illustrated or discussed herein may include doped semiconductor, but may instead include undoped semiconductor material. Further, any transferred layer or donor substrate or wafer preparation illustrated or discussed herein may include one or more undoped regions or layers of semiconductor material. Moreover, although the insulator between the stacked crystalline layers is identified as silicon oxide, other dielectrics may be utilized such as, for example, a low-k dielectric, carbon containing silicon oxides. Further, contacts may be formed, for example, as sidewall structures or end-wall structures, with various overlaps as required by the process and layout. Furthermore, the wiring of the peripheral circuits may be done using a lower melting point metal than tungsten, for example copper, and care taken not to exceed a damaging temperature during processing and may employ optical annealing. Rather, the scope of the invention includes both combinations and sub-combinations of the various features described herein above as well as modifications and variations which would occur to such skilled persons upon reading the foregoing description. Thus the invention is to be limited only by the appended claims.

What is claimed is:

1. A 3D IC based system, comprising:
 - a first layer comprising first transistors;
 - a second layer overlying said first layer, said second layer comprises a plurality of second transistors, wherein said second layer comprises at least one through second layer via having a diameter of less than 400 nm, and wherein at least one of said plurality of second transistors forms a two stable state memory cell comprising a back-bias region.
2. A 3D IC based system according to claim 1, wherein said back-bias region is disposed to one side of a channel region of said second transistors.
3. A 3D IC based system according to claim 1, wherein at least one of said second transistors comprise a side gate on one side and said back-bias region on the opposite side of a channel region.
4. A 3D IC based system according to claim 1, wherein said back-bias region comprises polysilicon.
5. A 3D IC based system according to claim 1, wherein at least one of said plurality of second transistors and one of said first transistors share a back-bias region.

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- 6. A 3D IC based system according to claim 1, wherein at least two of said plurality of second transistors are connected by a common doped mono-crystalline structure.
- 7. A 3D IC based system according to claim 1, wherein a first portion of at least one of said first transistors is self-aligned to a second portion of at least one of said plurality of second transistors.
- 8. A 3D IC based system, comprising:
a first layer comprising first transistors;
a second layer overlying said first layer, said second layer comprises a plurality of second transistors,
wherein said second layer thickness is less than 400 nm, and
wherein at least one of said plurality of second transistors forms a two stable state memory cell comprising a back-bias region.
- 9. A 3D IC based system according to claim 8, wherein said back-bias region is disposed to one side of a channel region of said second transistors.
- 10. A 3D IC based system according to claim 8, wherein at least one of said second transistors comprise a side gate on one side and said back-bias region on the opposite side of a channel region.
- 11. A 3D IC based system according to claim 8, wherein said back-bias region comprises polysilicon.
- 12. A 3D IC based system according to claim 8, wherein at least one of said plurality of second transistors and one of said first transistors share a back-bias region.
- 13. A 3D IC based system according to claim 8, wherein at least two of said plurality of second transistors are connected by a common doped mono-crystalline structure.

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- 14. A 3D IC based system according to claim 8, wherein a first portion of at least one of said first transistors is self-aligned to a second portion of at least one of said plurality of second transistors.
- 15. A 3D IC based system, comprising:
a first layer comprising first transistors;
a second layer overlying said first layer, said second layer comprises a plurality of second transistors,
wherein a first portion of at least one of said first transistors is self-aligned to a second portion of at least one of said plurality of second transistors, and
wherein at least one of said plurality of second transistors forms a two stable state memory cell comprising a back-bias region.
- 16. A 3D IC based system according to claim 15, wherein said back-bias region is disposed to one side of said of a channel region of second transistors.
- 17. A 3D IC based system according to claim 15, wherein at least one of said second transistors comprise a side gate on one side and said back-bias region on the opposite side of a channel region.
- 18. A 3D IC based system according to claim 15, wherein said back-bias region comprises polysilicon.
- 19. A 3D IC based system according to claim 15, wherein at least one of said plurality of second transistors and one of said first transistors share a back-bias region.
- 20. A 3D IC based system according to claim 15, wherein at least two of said plurality of second transistors are connected by a common doped mono crystal structure.

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